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Aircraft Technology Assessment Interim Report on the Status of the Gas Turbine Program

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AIRCRAFT TECHNOLOGY ASSESSMENT
INTERIM REPORT ON THE STATUS OF THE GAS TURBINE PROGRAM

December 16, 1975

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U. S. ENVIRONMENTAL
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Abstract

This report is a brief summary of the status of the aircraft gas turbine technology assessment program. It is a compendium of the information and technical data received from all organizations, government and industrial, involved in efforts to reduce aircraft engine exhaust emissions. The technical data have been reduced and presented in the format that the EPA intends to use in making its assessment of the growth of low emissions technology in aircraft gas turbines. This document is, therefore, only a prelude to the assessment topic in that actual assessment and recommendation are to be covered in the final report. ~~The final report will be available mid 1976 following the evaluation of new information.~~ The information contained herein and the thrust of the assessment are directed towards compliance with the EPA 1979 standards for newly manufactured engines. Consideration of compliance with the 1981 standards for newly certified engines will be given in later reports as the technology is advanced.

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Introduction

Section 231 of the Clean Air Act, as amended by Public Law 91-604, directs the Administrator of the Environmental Protection Agency to:

(1) investigate emissions of air pollutants from aircraft to determine the extent to which such emissions affect air quality and to determine the technological feasibility of control, and

(2) establish regulations for the control of emissions from aircraft or aircraft engines if such control appears warranted in the light of the investigation referred to above.

Furthermore, the Clean Air Act states that any such regulations can take effect only after sufficient time has been allowed to permit the development and application of the requisite technology.

The EPA has complied with both mandates of the Clean Air Act, first, by publishing a report, "Aircraft Emissions: Impact on Air Quality and Feasibility of Control," which concluded that the impact on air quality by aircraft was sufficient to justify control and that such control was technologically feasible, and second, by promulgating standards limiting the emissions from aircraft engines. These regulations have various compliance dates in the future commensurate with the leadtime then thought to be necessary to develop and apply the necessary technology.

In keeping with the spirit of the instructions to determine the technological feasibility of control and to allow sufficient time to permit the development and application of the technology, the EPA has established an Aircraft Technology Assessment Program for the purpose of monitoring the development of the low emissions technology for aircraft engines, both piston and gas turbine. This program for gas turbines was begun in July, 1974. In order to make the program as comprehensive as possible, a request for information was sent to all gas turbine engine manufacturers on October 1, 1974. Concurrently, contact was made with all other government agencies which were conducting or supporting relevant work to ensure that the EPA would stay abreast of their developments. Through the cooperation of the industry and the several government agencies working in this area, the EPA has received a considerable quantity of information from which it expects to assess the status of aircraft engine low emissions development. The present and future technology, the necessary leadtime, and the cost of compliance with the EPA regulations will all be reviewed. Additionally, the EPA expects to review the format of the regulations to assure that it properly reflects operational and technical realities (eg., is the admissible pollution level better normalized by the total impulse or energy over the cycle or simply by the rated thrust or power?). This document and the succeeding final report (planned for completion by mid 1976) do not address the issue of compliance with the 1981 regulations for large, commercial newly certified gas turbine engines. The status of the requisite technology is in a development stage and assessment is premature and unnecessary at this time.

This summary does not investigate the issue of cost of compliance largely because of the lack of hard information available. An EPA contractor, Arthur D. Little, Inc., has undertaken an attempt, as a part of its support effort to the EPA, to develop a data base from which cost estimates can be made. This work will be reported to the EPA in January, 1976.

This interim report intentionally draws no conclusions and makes no recommendations, but is rather a compendium of the information gathered thus far by the EPA, reduced and presented in the manner that the EPA finds useful in conducting this assessment. The EPA decided that conclusions or recommendations would be premature at this time because of the forthcoming public hearing. This public hearing focuses principally on the EPA proposed regulation of large in-use aircraft (described in the Federal Register, Volume 38, Number 136, July 17, 1973, 19050) and secondarily on the aircraft regulations in general (the notice for the hearing, Federal Register, Volume 40, Number 216, p. 52082, lists several topics the EPA is particularly interested in having addressed). It is expected that this hearing will produce useful information for incorporation into the assessment program. The reader will find that there are missing data in many instances despite the quantity of information received. The EPA is hopeful that many of these gaps will be filled in prior to the publication of the final report.

The report contains summaries of the emissions performance of existing gas turbine engines, research and development programs leading to low emissions, low emissions design concepts and how they operate, best demonstrated performance of engines, and best demonstrated and retrofitable (readily capable of installation into existing hardware). There are also discussions of comparative technology and leadtimes necessary for compliance with the 1979 regulations for newly manufactured gas turbine engines.

Aircraft piston engines are not covered in this document as the approach to performing the assessment for such engines is different from that for gas turbine engines reported herein. Also, such an assessment would be difficult to perform at this time owing to the scarcity of data. It is presently anticipated, however, that sufficient data will be compiled in time to include an evaluation of piston engine development in the final report.

Section 2 - Summary of Standards and Emissions Performance of Production Engines

The aircraft emissions standards (40 CFS, part 87, described in FR Vol. 38, N. 136, July 17, 1973, p. 19088) describe standards for the emission of unburnt hydrocarbons (HC), carbon monoxide (CO), oxides of nitrogen (NOx), and visible smoke from aircraft gas turbine engines, newly manufactured and newly certified. The standards for newly manufactured gas turbine engines go into effect January 1, 1979, a date selected to allow time for proper development of the requisite technology, while the more stringent standards for newly certified gas turbine engines go into effect two years later, January 1, 1981 (As a newly certified engine would allow more latitude to the designer to incorporate low emissions features such as catalytic burners or low fuel consumption engine characteristics, standards for such engines are set commensurately lower). In addition, there are smoke standards applicable to certain in-use engines at earlier dates. The standards are directed at the reduction of aircraft emissions including smoke in the vicinity of major airports which are in or adjacent to major urban areas wherein aircraft emissions will contribute to the general degradation of the air quality.

In general the standards themselves apply not to the aircraft, but to the engines. The approach to regulate the engines directly instead of the aircraft was taken to minimize the enforcement effort as the same engine is often used in several aircraft applications. Furthermore, all aircraft in which a given engine might be used have generally similar flight profiles and hence have similar flight profiles and hence have similar emissions signatures in the airport environs.

In accordance with the latitude permitted by the Clean Air Act (1970), EPA found it desirable to establish classes of aircraft and corresponding engine classes to which different sets of standards would apply as determined by the technical, economic, and safety constraints relevant to each class. The classes established are as follows:

Table 2-I Summary of Aircraft Classes

Class	Type	Aircraft Application
P1	Piston engines (excluding radials)	Light general aviation
P2	Turboprop engines	Medium to heavy general aviation; some commercial air transport
T1	small turbojet/fan engines	General aviation jet aircraft

T2	Large turbojet/fan engines intended for subsonic flight	Commercial subsonic transports
T3, T4	Special classes applying to specific engines for the purpose of instituting early smoke standards	Commercial subsonic transports
T5	Large turbojet/fan engines intended for supersonic flight	SST
APU	Gas turbine auxiliary power units	Many turbojet/turboprop

Piston engines are not considered in this report.

The specific engines within each class to which this technology assessment is addressed are listed in Table 2-II along with their present emissions levels and production potential after January 1, 1979, the deadline for compliance for newly manufactured engines.

The emissions are described by an EPA parameter (EPAP) which is defined in the aircraft standards. Briefly, it is a measure of the total emission of a particular pollutant produced by an engine over a typical landing-takeoff (LTO) cycle normalized with respect to the total impulse (for jet thrust engines) or total energy (for shaft power engines) produced over that cycle. As such, larger engines are permitted proportionally larger amounts of total emissions over smaller engines.

Production potential is not usually available in hard figures. Generally though, the production of all engines can be grouped into four categories for EPA purposes.

Category	Situation
I	Engines already out of production; engines certain to be out of production by 1/1/79.
II	Engines at or near the end of their production run by 1/1/79. The few, if any, units produced after 1/1/79 would not be sufficient to amortize the development and certification cost of a low emissions combustor.

III	Engines in the broad middle of their production run. It is possible to amortize the necessary development and certification costs over the remaining production. It is equally possible to consider a cost-effective retrofit of the units produced prior to 1/1/79; there are sufficient units to amortize that development and certification costs and to realize significant air quality gains.
IV	Engines beginning their production run shortly before or after the 1/1/79 implementation date. There are insufficient engines built prior to the deadline to warrant a retrofit program.

Table 2-II

Emissions Performance - Production Engines

Class	1979 Standard HC	 CO	 NOx	Engine	Size	Manufacturer*	Baseline Emissions HC	 CO	 NOx	 Sk/Std**	Production *** after 1/1/79
T1	1.6	9.4	3.7	TFE 731-2	3500-3700 lbs	AiResearch	6.6	17.5	5.0	36.2/40	III
	(pounds of pollutant/1000 pound-thrust-hours/cycle)			-3			4.0	15.9	6.1	45/40	III
				JT15D	2200-2500 lbs	UACL	8.65	29.74	4.10	14.1/43	III
				ALF502D	6,500 lbs	Avco-Lycoming	1.9	12.0	4.2	20/33	IV
				JT12A	3000-3300 lbs	P&WA	No data				I
				CF700	4200-4300 lbs	GE	9.12	93.93	2.2	24/38	I
				CJ610	2850-2950 lbs	GE	14.69	154.89	2.74	44/35	I
				M45H	7,500 lbs	Rolls-Royce/ Snecma	9	52	4	-	III, IV
				RB401		Rolls-Royce/ P&WA	.2	10.2	3.6	-+	IV +Predicted
T2	0.8	4.3	3.0	JT9D	45,000-53,000 lbs	P&WA	4.8	13.8	5.7	12/20 5/19	III
				JT10D		P&WA Rolls Royce	New engine				IV
				CF6-6	41,000	GE	3.41	10.00	7.20	13/21	III
				-50	54,000 lbs		4.26	10.81	7.67	13/19	III
				CFM56	22,000 24,000 lbs	GE/Snecma	1.6	13.8	4.4	25/24	IV
				RB 211-22B -524	42,000-50,000 lbs	Rolls Royce	No data		6.20	/21 /20	III
				Spey-MK/511	9,900-12,550 lbs	Rolls Royce	6.17	16.02	7.21	/30 /27	II, III
T3	Same as T2			JT3D	17,000-19,000 lbs	P&WA (Smokey) (Smokeless)	34.2 18	40.8 26.2	3.8 5.6	53/none 16/25	I
T4	Same as T2			JT8D	14,000-19,000 lbs	P&WA	3.9	16.0	7.6	28/30	II, III
T5	Standards not yet promulgated			Olympus 593	38,000 lbs	Rolls Royce/ Snecma	16.2	67	8.9	28	III

* Abbreviations

UACL- United Aircraft of Canada Limited
P&WA- Pratt & Whitney Aircraft
GE - General Electric

** SK/STD- Smoke level/ Smoke Standard

*** R[illegible]o te[illegible] defi[illegible] of [illegible]ries

Table 2-11 continued

Class	1979 Standard HC	 CO	 NOx	Engine	Size	Manufacturer	Baseline Emissions HC	 CO	 NOx	 Sk/Std	Production after 1/1/79
APU	0.4	5.0	3.0	GTCP85-98CK	260-290 eshp	AiResearch	.20	7.53	5.75	N.A.	III
	(pounds of pollutant/1000 horsepower-hour of power output)			GTCP30-92		AiResearch	.14	5.26	3.71	"	III
				GTCP36		AiResearch	.30	19.83	5.24	"	III
				GTCP165		AiResearch	No data			"	III
				GTCP660		AiResearch	.20	7.92	4.87	"	III
				TSCP700		AiResearch	.16	.81	6.05	"	III
				ST6		UACL	.27	2.63	4.83	"	III

Class	1979 Standard HC	 CO	 NOx	Engine	Size	Manufacturer	Baseline Emissions HC	 CO	 NOx	 Sk/Std	Production after 1/1/79
P2	4.9	26.8	12.9	PT6A	580-1170 eshp	UACL	37.5	53.5	5.9	17.3/48	III
	(pounds of pollutant/1000 horsepower-hours/cycle)			-27 -41	75 eshp 1089 eshp		78-95	106-121	6.8-5.8	22.2/48	III
				TPE331-3	665-840 HP	AiResearch	57.1	44.4	7.8	19.8/46	III
				250	330-400 HP	Allison	42.48	111.0	4.56	30/50	III
				501-D22A	4700 eshp	Allison	9.7	19.0	5.4	55/29	II, III
				T5321A	1800 eshp	Avco-Lycoming	2.3	17.3	6.0	17/37	III
				LTP101	610 eshp	Avco-Lycoming	12.1	34.8	5.3	40/50	IV
				PLT27	2000 shp	Avco-Lycoming	.3	3.1	12.8	0/36	IV
				Dart	1860-3250 eshp	Rolls-Royce	No data				I

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Section 3 - Programs for Reduction of Engine Emissions

This section summarizes all the programs known to the EPA which bear upon the compliance of aircraft gas turbine engines with the EPA regulations. These programs are broken into two categories, engine related programs and combustor research programs. The former are directed exclusively towards the 1979 EPA standards and the latter are applicable to all the standards in general as such programs serve more to advance understanding than to concoct a specific solution.

Engine Related Programs

Government Sponsored Engine Programs

The government has sponsored and continues to sponsor several major engine related low emissions combustor development programs. A summary of these programs is provided in Table 3-I. Research and development in these programs were conducted by private companies, and in some cases the company partially funded these programs on a cost sharing basis.

Industry Sponsored Engine Programs

Most of the manufacturers have initiated programs of their own to identify and refine the technology necessary to satisfy the 1979 standards. In general two approaches were taken. These were modification to current production hardware, and new combustor design concepts. Again, as indicated above, some of these programs were conducted on a cost sharing basis with the government. A summary of these programs is provided in Table II.

Table 3-I

Engine Related Programs - Government Sponsored

Agency/Company	Objective	Status	Funding/Duration
NASA Lewis/Garrett AiResearch (Small Jet Engine Program)	Demonstrate combustor technology, for the TFE 731 engine, which is capable of meeting T1 class standards.	Phase I (combustor screening of three phases is 70 percent complete. The combustor concepts being screened are: 1) modified existing combustor 2) airblast system (meets HC and CO standard) 3) premix/prevaporization	600K Phase I*/FY 75-76 (17 months)
NASA Lewis/Pratt & Whitney Aircraft (Can-Annular Program)	Demonstrate combustor technology, for the JT8D engine, which is capable of meeting the T4 class standards.	Phase I (combustor screening) of two phases is approximately 80 percent complete. The combustor concepts being screened are: 1) modified existing combustor (meets HC standard) 2) vorbix combustor 3) premix/prevaporization	513K Phase I*/FY 75-76 (16 months)
NASA Lewis/Detroit Diesel Allison (Turboprop Program)	Demonstrate combustor technology, for the 501D-22 engine, which is capable of meeting the P2 class standards.	Phase I (combustor screening) of three phases is approximately 80 percent complete. The combustor concepts being screened are: 1) reverse flow 2) staged fuel 3) prechamber (meets HC, CO, NOx standard)	242K Phase I*/FY 75-76 (13 months)
NASA Lewis/General Electric (ECCP)	Demonstrate combustor technology, for the CF6-50 engine, which is capable of meeting the 1979 T2 class standards.	Phase III (engine demonstration) of three phases is approximately 30 percent complete. Pursuing double annular combustor concept. (Meets: HC, CO standards) (Fails: NOx standard)	1000K Phase I*/FY 73-74 (18 months) 950K Phase II*/FY 75 (12 months) 1200K Phase III*/FY 76 (12 months)
NASA Lewis/Pratt & Whitney Aircraft (ECCP)	Demonstrate combustor technology, for the JT9D engine, which is capable of meeting the 1979 T2 class standards.	Phase III (engine demonstration) of three phases is approximately 30 percent complete. Pursuing vorbix combustor concept. (Fails: HC, CO, NOx standards)	800K Phase I*/FY 73-74 (19.5 months) 950K Phase II*/FY 75 (12 months) 1200K Phase III*/FY 76 (14 months)
Army/Detroit Diesel Allison	Develop and demonstrate technology sufficient to obtain a 50 percent overall reduction in T63 (class P2) engine emissions with no increase in any individual pollutant	Program completed. Best concept is the premix combustor. (Meets: HC, NOx standards) (Fails: CO standard)	97K/FY 72-73 (12 months)

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* Government share of cost shared expenses

Table 3-I continued

Agency/ Company	Objective	Status	Funding/Duration
Army/Williams Research /Garrett AiResearch /Pratt & Whitney Aircraft /AVCO Lycoming	Develop new high performance turboshaft engines with low emissions. Engine has application as turboprop (class P2) or as an APU.	Program nearing completion Williams concept - meets standards AiResearch concept - fails standards Pratt & Whitney concept - no data AVCO Lycoming concept - meets standards	Unknown
Army/Detroit Diesel Allison	Refine best designs and concepts from T63 program above and test in a Model 250-C-20B (class P2) engine.	Testing has been completed and data is in final stages in preparation for report. No data available.	293K/FY 74-76 (23 months)
EPA/Garrett AiResearch	Develop full scale engine data to determine the effects of ambient conditions on emissions for the TPE331 (Class P2) and GTCP85 (APU) engines.	Testing has been completed and a final report is being prepared. The emissions standards were achieved in the TPE331 engine by rescheduling the fuel flow to operate only on primary atomizers at taxi-idle.	Joint project 170K TPE331 extension 16K } FY75-76(10 months)

Table 3-II

Engine Related Programs - Industry Sponsored

Company	Objective	Status	Funding/Duration
Garrett AiResearch	Develop combustor technology for the TPE 331 engine which allows it to meet P2 class standards.	Best concept is rescheduling fuel flow to operate on the primary atomizers only at taxi-idle. (Meets: HC, CO, NOx standards)	Unknown/1973-1974 (2 Years)
Garrett AiResearch	Develop combustor technology for the TFE 731 engine which allows it to meet T1 class standard.	Best concept demonstrated was the air assisted fuel nozzles.	
Garrett AiResearch	Develop combustor technology for APUs which allow them to meet the APU standard.	Best concepts demonstrated were: GTCP 36 - airblast - meets HC standard; fails CO and NOx GTCP 85 - increased fuel spray cone angle - meets HC and CO standard; fails NOx GTCP 30 - } TSCP 700 - } production combustor - meets HC and CO standard; fails NOx GTCP 660 - production combustor - meets HC standard; fails CO and NOx	
Garrett AiResearch (Small Jet Engine Program)	Demonstrate combustor technology for the TFE-731 engine, which is capable of meeting the T1 class standards	See Table I	Cost shared with NASA Company share unknown See Table I
Pratt & Whitney Aircraft	Develop combustor technology for the JT9D engine which allows it to meet 1979 T2 class standards.	Best concept demonstrated was aerating fuel nozzles combined with modified airflow distribution. (Meets: HC, CO standards) (Fails: NOx standard, unless water is used.)	Unknown/1972-1975 (3 Years)
Pratt & Whitney Aircraft (ECCP)	Demonstrate combustor technology for the JT9D engine which is capable of meeting the 1979 T2 class standards	See Table I	Cost shared with NASA Company share unknown See Table I
Pratt & Whitney Aircraft (Can-Annular program)	Demonstrate combustor technology for the JT8D engine which is capable of meeting the T4 class standards.	See Table I	Cost shared with NASA Company share unknown See Table I
Pratt & Whitney Aircraft	Develop low smoke combustor for JT3D (class T3) engine.	Best concept demonstrated combined delayed dilution with aerating fuel nozzles. This concept significantly reduced HC and CO while increasing NOx. (Fails: HC, CO, NOx standards)	Unknown/1968-1974 (6 Years)

Table 3-II continued

Company	Objective	Status	Funding/Durations
Pratt & Whitney Aircraft		JT12A class T1 engine is expected to be out of production and therefore no effort was made to reduce emissions from it.	
United Aircraft of Canada Limited	Develop low emissions combustor technology for the PT6A-27 and -41 (class P2) engines	The best emissions results were obtained with the combustor airflow redistributed. Results were: PT6A - 41 - meets HC, CO, and NOx standard PT6A - 27 - meets CO and NOx standard; fails HC	190K/1973 (1 Year)
United Aircraft of Canada Limited	Develop low emissions combustor technology for the JT15D (class T1) engines	Reducing the fuel spray cone angle was the most effective concept demonstrated was the rich primary/delayed dilution concept. (Meets: HC standards) (Fails: CO, NOx standards)	255K/1971, 1973 (2 Years)
General Electric	Determine the most effective method of reducing emissions in the CJ610/CF700 (class T1) engines	Reducing the fuel spray cone angle was the most effective concept demonstrated. With this method HC levels were reduced 60 percent relative to current engine (still fails to meet standard) while NOx remained acceptable (meets standard) and CO was unchanged (fails to meet standard).	Unknown/1973-1974 (2 Years)
General Electric (ECCP)	Demonstrate combustor technology for the CF6-50 engine, which is capable of meeting the 1979 class T2 standard.	See Table I	Cost shared with NASA Company share unknown See Table I
Detroit Diesel Allison (Turboprop Engine Program)	Demonstrate combustor technology for the 501D-22 engine, which is capable of meeting the P2 class standards.	See Table I	Cost shared with NASA FY 75-76 Company share 81K Phase I (13 months)

Combustor Research Programs

Government Sponsored Combustor Research Programs

Several non-engine related combustor development programs have also been sponsored by the government. These programs include grants to private industry, research laboratories and universities, and NASA and Air Force "in-house" programs. A summary of these programs is provided in Tables III, IV, and V.

Also, the government has sponsored a number of analytical combustor modeling studies to support the development of necessary low emissions technology. These studies have also been conducted by private industry, research laboratories and universities, and NASA and the Air Force. A summary of these programs is provided in Tables VI, VII, and VIII.

Industry Sponsored Combustor Research Programs

Although such efforts certainly exist within the industry, the EPA has no explicit knowledge of them, perhaps because they may be appendages to larger engine related programs.

Table 3-III

Government Sponsored Combustor Development Programs

Private Industry Non Engine Related

Program/Sponsoring Agency	Investigator	Objective	Status	Funding
Augmentor Emissions Reduction Technology/NASA Lewis	General Electric Company	Reduce emissions from duct burning engines	Approximately 25 percent complete	500K FY 75-76
Advanced Concepts to Reduce NOx in Aircraft/NASA Lewis	Solar Division of International Harvester	Reduce NOx at supersonic cruise conditions	Experimental testing completed. Report being finalized.	250K FY 74-75
Low NOx Emission Combustor/NASA Lewis	General Applied Science Laboratory	Demonstrate that premix concept will result in low NOx at supersonic cruise conditions.	A final report is being prepared.	78K FY 74 75K FY 75 40K FY 76
Full Annular Low NOx Emission Combustor/NASA Lewis	Solar Division of International Harvester	Investigate application of jet-induced-circulation combustor concept to full annular combustor	Single source RFP has been issued.	
Fundamental Low Power Emission Study/NASA Lewis		Study advanced concepts for reducing low power emissions that will permit the design of combustors meeting the 1981 standards.	RFP to be issued by first quarter CY'76	
Combustor Exhaust Odor Intensity and Character Study/NASA Lewis	A. D. Little	To determine the intensity of odors of exhaust gases from various turbojet engines or combustors at several engine operating conditions, and to determine ambient odor intensities at strategic airport locations.	Program completed.	114K FY 72-73 25K FY 74-75
Supersonic Cruise Combustor Pollution Technology/NASA Lewis	Pratt & Whitney Aircraft General Electric Company	To investigate combustion concepts specifically designed for low NOx emission at supersonic cruise operating conditions. This is an addendum to ECCP.	Program completed.	200K to each investigator FY 73-74
Advanced, High-Temperature-Rise Combustor/AFRDL	Garrett AiResearch	Minimize NOx, CO, and HC and smoke levels for 2-5 lb/sec combustors at 12-16 atm inlet pressure	Project completed.	415K FY 70-73
Low Emission Jet Combustor/AFRDL	Jet Propulsion Laboratory	To generate and evaluate unconventional combustor design concepts.	Program is 60 percent completed.	Unknown
Low NOx Emission Combustor for Automobile Gas Turbine Engines/EPA-AAPS	United Aircraft of Canada Limited	Develop reduced emission and low fuel economy automotive gas turbine engine.	Project completed.	248K FY 71-74
Hydrogen Enrichment for Low Emission Jet Combustion/NASA Washington, D.C.	Jet Propulsion Laboratory	Experimentally evaluate the H_2-enrichment concept with a research combustor.	Currently, experimental evaluation of the H_2-enrichment concept is underway with a research combustor utilizing premixed H_2/fuel/air mixtures.	150K/year FY 73, 74, 75
Independent Research and Development/DOD	Engine contractors with DOD	Private industry is granted a limited amount of government funds to conduct independent research programs some of which will support low emissions studies		Unknown

Table 3-IV

Government Sponsored Combustor Development Programs

University Grants

Program/Sponsoring Agency	Investigator	Objective	Status	Funding
Mixing in High-Intensity Combustors/ NASA Lewis	Prof. R.A. Strehlow at University of Illinois	To develop means to probe molecular-level mixedness in high-intensity combustors	The effect of turbulence on molecular mixing is being investigated.	51K/year FY 73, 74, 75, 76
Flow Processes in Combustors/ NASA Lewis	F. Gouldin, S. Leibovich, F. Moore at Cornell University	Measure and predict velocity and turbulence levels in swirling recirculating flows with and without chemical reactions.	Several experiments in progress	64K FY 75 75K FY 76
Study of Techniques for Lean Combustion Systems/NASA Lewis	M. Branch, A. Oppenheim, R. Sawyer at University of California, Berkeley	Study combustion processes of fuel lean, turbulent flames at realistic gas turbine conditions to develop stabilization techniques and improve idle performance.	Assembly of test equipment is in progress.	75K FY 75 73K FY 76
Influence of Intensity and Scale of Turbulence on Emission Concentrations in the Primary Zone of a Gas Turbine Combustor/NASA Lewis	Prof. A.A. Kovitz at Northwestern University	To determine the effect of turbulence on emission concentrations within a premixed combustor using gaseous propane as a fuel.	Project has been completed and a technical report has been prepared.	48K/year FY 72, 73, 74
Technology Support/EPA	Prof. A.M. Mellor at Purdue University	To conduct low emissions research to aid in the development of low emission technology.	Currently, a fuel nozzle study is being conducted.	33K FY 72 40K FY 73 40K FY 74 60K FY 75

Table 3-V

Government Sponsored Combustor Development Programs

NASA/Air Force

Program	Investigator	Objective	Status	Funding
Evaluation of Techniques for Pollution Reduction	NASA Lewis Research Center	Reduce emissions from turbojet combustors and reheat burners.	Continuing "in-house" effort. The effect of exhaust gas recirculation was examined and a final report is in preparation. Study of catalytic combustors was studied and the report issued. Altitude emissions of refanned JT8D was studied and the report issued.	250K FY 73 195K FY 74 50K FY 75 100K FY 76
In-house Exhaust Emissions Investigation	AFAPL	Provide limited investigated to further understanding of aircraft engine exhaust problems.	Program began April 1975 and will continue for 3 years.	Unknown
Swirl Car Combustors	NASA Lewis Research Center	Develop short-length high performance turbojet engine combustors having low levels of exhaust emissions suitable for Mach 3 flight.	Continuing "in-house" effort.	165K FY 73 125K FY 74 40K FY 75
Twin-Ram Induction Combustors	NASA Lewis Research Center	Develop a short double-annular combustors for advanced turbojet engines.	Task completed FY 74. Reports on final stage is complete.	50K FY 74
Basic Pollution Research	NASA Langley Research Center	a) Study reaction kinetics of NO formation in fuel rich systems behind shock waves. b) Study effort of very high pressure on NOx formation. c) Study the kinetics of soot formation and decay using laser light-scattering techniques. d) NOx formation studies in a jet-stirred reactor.	Continuing "in-house" effort.	50K FY 73 23K FY 74 60K FY 75
Single Combustor Rig Investigation of Turbine Engine Exhaust Emissions	AFAPL	To investigate novel control and measurement techniques.	Continuing "in-house" effort.	Unknown
Gas Turbine Catalytic Combustor	AFAPL & Engelhard Industries	Investigate the catalytic combustor concept.	Continuing "in-house" effort.	Unknown
Premixed Variable Geometry Combustors	NASA Lewis Research Center	Investigate the pollutant reductions possible with premixed, variable geometry combustors.	Project Completed.	125K FY 74
Multiple Point Fuel Distribution	NASA Lewis Research Center	Study ways of dividing and simultaneously regulating one flow stream into several equal flow multiple streams.	Project Completed.	150K FY 73

Table 3-VI

Government Sponsored Combustor Modeling Programs

Private Industry

Program	Investigator	Objective	Status	Funding
Combustors Design Criteria Validation/AMRDL	Garrett AiResearch	Develop and validate existing analytical combustor design procedures which can be used to significantly shorten the design time of 2-5 lb/sec. combustors.	Preliminary version of computer program is operational.	
Development of a 3-D Combustor Flow Analysis/AFAPL/FAA	United Technologies Research Center	To modify and extend an existing three-dimensional Navier-stokes calculation procedure which includes the effects of chemical reaction, turbulence transport, radiation energy flux, and droplet burning, and vaporization.	Program is approximately 70 percent completed.	25K FY 74 91K FY 75
Low Power Turbopropulsion Combustor Emissions/AFAPL	Pratt & Whitney Aircraft	To identify and develop improved component design techniques which will increase part-power performance.	Project completed.	100K FY 71 600K FY 72 315K FY 73 177.6K FY 74
Combustor Flow Analysis Procedure AFAPL/FAA	United Aircraft Research Laboratory	To refine an existing analytical technique and develop a computational procedure for predicting combustion system performance.	Project completed.	85.dK FY 72
Analysis and Investigation of Exhaust Emissions from Non-Afterburning Aircraft Gas Turbine Engines During High Power/AFAPL	Pratt & Whitney Aircraft	Optimize design features through insight gained from analytical modeling of the combustor at low power and from experimental results.	Project completed.	75K FY 73 25K FY 74
Turbojet Combustor Pollution Formation/NASA Lewis	General Applied Science Laboratory	Develop a modular computer program to describe the coupled flow and combustion kinetics in a turbojet combustor.	Project completed.	50K FY 72 19.5K FY 73
Analysis of Combustion Systems with Swirl/NASA Lewis	Advanced Technical Laboratory	Perform numerical modeling of swirling flows using finite difference techniques for predicting the effect of swirl on combustor performance and emissions.	Project completed.	84K FY 71-73

Table 3-VII

Government Sponsored Combustor Modeling Programs

University Grants

Program	Investigator	Objective	Status	Funding
Study of Air Pollution from Aircraft/NASA Lewis	John B. Heywood at MIT	To predict NOx and CO levels in combustors and to investigate fuel atomization, fuel vaporization, and the mixing process inside the combustor.	Continuing research effort.	66K FY 74 79K FY 75 115K FY 76
Study of Parameters Affecting Emissions of Gas-Turbine Engines/NASA Lewis	Prof. C.W. Kauffman University of Cincinnati	Analyze combustor emission data and formulate a mathematical expression that correlates measured emissions with primary operating conditions.	Data in process of being analyzed.	33K FY 75-76
Basic Chemistry of Aircraft Pollutants/NASA Lewis	Professor A. Berlad SUNY-Stonybrook	Survey current reaction rate literature on chemical reaction affecting atmospheric ozone levels, establish analytical model of ozone balance in the atmosphere, and indicate required experimental rate data needed to solve model.	Project completed.	48K FY 73-75

Table 3-VIII

Government Sponsored Combustor Modeling Programs

NASA/Air Force

Program	Investigator	Objective	Status	Funding
Turbine Engine Exhaust Emissions Technology	AFAPL	Develop ambient temperature and humidity correction factors for CO and HC.	Project completed.	40k FY 72-73
Aircraft Engine Emissions Correlation Technique	Air Force Weapons Laboratory	To predict CO, HC, and NOx and particulate emissions indicies for turbine engines used by the Air Force.	Continuing "in-house" effort.	2K FY 74-75 5K FY 76
Three Dimensional Combustion Flow Analysis	Wright-Patterson AFB	Develop a mathematical model of the combustion process for annular and can-annular combustors.	Project completed.	80k FY 72-74
Combustor Analytical Modeling of Pollution Formation	NASA Lewis Research Center	To study the effects of mixing and fuel preparation on the formation of emissions.	Project completed.	50k FY 74

Section 4

Low Emissions Technology Concepts

Considerable testing of several combustor concepts has been conducted by the engine manufacturers. These efforts have been mainly in fuel preparation techniques, especially nozzle design and fuel distribution concepts, and in air distribution techniques. No single technique tested was effective in simultaneously reducing NOx, HC and CO over the operating range of an engine to the levels required by the 1979 standards. Some, but not all, of the concepts tested did, however, demonstrate potential to meet the 1979 standards for a given pollutant. Reduction of all three emissions to the levels required by the standards will probably require more than one concept to be designed into a combustor. A summary and discussion of the concepts tested is presented below.

Although often simple in concept, many of these control techniques are nonetheless difficult to apply in practice. Often, techniques which involve combustor modification are detrimental to the combustor performance in non-emissions related areas such as altitude relight, durability, etc. An acceptable design is, therefore, often a compromise between conflicting goals. While economic goals can be compromised, safety goals cannot, so usually an emissions control technique is in practice less effective than its potential.

I. Fuel Preparation

1. Airblast - The pressure differential that exists between the compressor and the combustor is employed to achieve high velocity air through a venturi system at the combustor inlet. This high velocity air is directed towards the fuel injectors to help break up the fuel droplets and thus eliminates locally rich hot spots. By eliminating the locally rich hot spots, NOx levels should be reduced. Improved atomization at intermediate power levels such as approach should lead to reductions in HC and CO levels, also.

This concept is relatively simple since it requires only the addition of the venturi tubes, and a corresponding balance of airflow to maintain the fuel-air ratio. No other hardware systems have to be modified.

Success in NOx reduction by utilizing this technique has varied among the manufacturers. Results of testing combustors equipped with airblast fuel nozzles indicate that NOx may even increase as a result of the better combustion efficiency. At low power the pressure differential is reduced and hence the pressure differential and the air velocity around the fuel injectors is reduced. Therefore, the airblast effect on fuel atomization is not as effective at low power where the bulk of the HC and CO is formed.

2. Air-assist - An alternative to the airblast technique is the air-assist concept. This system is the same as the airblast system except for the method used in creating the high velocity air around the fuel injectors. In the air-assist technique compressor air is diverted and compressed externally, and then discharged around the fuel injectors. Thus the high velocity airblast effect is maintained at all power levels especially at idle wherein the airblast technique is ineffectual. This technique should, therefore, be very effective in reducing HC and CO emissions at low power and in low pressure ratio engines.

The results of experimental testing of combustors equipped with air-assist systems indicate that substantial reductions in low power levels of HC and CO emissions can be achieved with this technique. However, NOx may increase due to a higher flame temperature.

The use of air assist would have a major impact on aircraft hardware systems because of the requirement to redistribute and compress externally with auxiliary compressions a part of the compressor airflow.

3. Premix - Fuel and air are mixed in a prechamber prior to entering the primary combustion zone. This premixing allows combustion to occur at leaner conditions where NOx formation rates are slower. Experimental test results indicate that NOx reductions can be achieved where there is sufficient combustor inlet temperature to vaporize fuel droplets in the prechamber. This means that this technique is most applicable to high pressure ratio engines, which produce the required high combustor inlet temperatures.

With the premix concept careful attention must be given to the prechamber exit conditions. Exit velocities of the fuel-air mixture must be high enough at all power levels to prevent flashback which is very damaging to the liner and the nozzle. Also, in creating a lean primary zone combustor stability may be a problem leading to altitude flameout and difficulties in relighting.

The premix concept requires a significant change to the combustor liner geometry since the premix chamber must be included in the combustor. In some cases this has led unavoidable to a longer overall combustor and thus in the combuster outer casing.

4. Fuel Atomization - Pressure atomizer nozzle design changes can lead to changes in the character of the fuel droplet size distribution. This in turn affects the evaporation time and strongly influences the amount of HC left unburned. To a lesser extent, the change in the evaporation rates affect the local fuel-air mixture ratio and thus, the local temperature which would likely affect the CO and NOx levels.

Decreasing the flow number (equal to the fuel flow rate divided by the injector pressure differential) reduces the droplet size and in turn the evaporation time. This results in a hotter local mixture which consumes the HC and CO. NOx, however, increases. This approach is not universally profitable, however, as experiments indicate that at low combustor inlet temperatures, no degree of atomization will improve the droplet evaporation as there is simply insufficient heat available.

Incorporation of this approach into a hardware system involves changing the pressure differential across the injector unless combined with the control technique of fuel sectoring (see below, II-3) as otherwise the fuel flow rate is fixed at each power setting. Changing the pressure differential requires only a new set of valves and possibly a pressure boost in the fuel pump.

II. Fuel Distribution

1. Fuel staging - The combustor is divided into two regions, each having its own fuel injection system. These are termed the pilot stage and the main stage. At low power, fuel is supplied only to the pilot stage, thereby allowing twice the fuel/air ratio that would be possible if the fuel were distributed throughout the combustor. This mixture is then able to burn hotter, enhancing the CO to CO_2 conversion and droplet evaporation (aiding HC burning).

At high power, the fuel is distributed between the two stages in such a way so as to minimize the peak temperature. This aids in preventing NOx production. Generally, though, this type of combustor also incorporates air distribution features (See III below) or fuel preparation features which further aids low NOx levels. Staging requires two fuel injection locations and adds to the complexity of the fuel supply system and the fuel control. The combustor liner is also more complex with additional cooling and temperature profile problems.

2. Nozzle Design - Pressure atomizer nozzle design changes intended to optimize the fuel spray cone angle, and thus the distribution of fuel in the primary zone, are relatively easy to incorporate into a combustor.

Decreasing the angle of a wide angle spray cone reduces wall wetting which in turn helps to reduce HC. Increasing the angle of a fuel rich narrow angle spray cone is also effective in reducing HC and CO levels since more complete combustion results from the better fuel distribution. An optimum angle must be found empirically.

There is no impact on the system hardware as only the fuel nozzle is changed and the new one is no more complex than the old.

3. Fuel Sectoring - Fuel sectoring is a method to improve the combustion conditions at idle and thereby improve HC and CO emissions. In essence it is like fuel staging in that fuel is selectively removed from part of the combustor and injected into another in order to achieve a desirable fuel/air ratio. Specifically, at idle when the combustor is burning quite lean and at a low flame temperature, the combustion efficiency is poor, resulting in much HC and CO, because of inadequate heat to vaporize the fuel and to stimulate the $CO \rightarrow CO_2$ reaction. This problem is resolved by cutting off the fuel entirely to part of the combustor (usually half, and injecting it with the rest of the fuel into the remaining part of the combustor. This has two beneficial effects: (1) the flow number of the nozzle is necessarily reduced, improving atomization and (2) the fuel/air ratio is increased (richened) so that a hotter flame exists, improving vaporization of the fuel and enhancing the $CO \rightarrow CO_2$ reaction.

Hardware changes are minimal and involve only replacement of half the fuel nozzle valves with ones designed to open at a higher pressure. As such this control technique is particularly attractive for retrofit, especially in view of its nearly universal usefulness.

III. Air Distribution

1. Lean Primary - The lean primary zone is achieved by introducing a larger percentage of the total combustor airflow into the primary zone (where the fuel is injected). This creates a leaner, and therefore, cooler flame which prevents the formation of NOx by lowering the $N_2 \rightarrow$ NO reaction rate. An emissions penalty is paid, however, through increased CO, a result of the lower temperature quenching the $CO \rightarrow CO_2$ reaction. This tradeoff has been witnessed in experiments. Used by itself, therefore, this concept is generally unacceptable. If CO can be controlled by some other combustor concept, then leaning the primary can be adapted for NOx reduction.

As with the premix concept discussed above, a lean primary zone is subject to flame stability problems especially at low powers when the primary is at its leanest condition. Also, the larger amounts of airflow into the primary leave less air to be used further down the combustor for cooling the liner or adjusting the temperature profile into the turbine. This could lead to durability problems.

2. Rich Primary - Theoretically, reducing the primary airflow increases the local fuel/air ratio and hence the primary zone temperature. At low power, this is beneficial in that the higher temperature enhances the $CO \rightarrow CO_2$ conversion and aids in fuel droplet evaporation, thereby improving the consumption of HC. NOx may be expected to increase slightly. At high power, the rich primary is very hot, producing large quantitites of NOx. If the equivalence ratio is greater than one in the primary

zone, smoke becomes a problem, requiring complicated air flow patterns in the secondary and dilution zones to consume it. Very limited results of testing this combustor concept verify the expected CO reductions and the ensuing smoke problem.

3. Delayed Dilution - By delaying the introduction of dilution air, a longer combustion zone at intermediate temperatures is provided. This increases the residence time of the reactants which allows the CO to CO_2 conversion to approach equilibrium and for unburnt hydrocarbons to be consumed. The temperature in the intermediate zone should be, however, low enough so that NOx formation rates are slow. Very limited test data indicates that CO and HC are reduced, as anticipated, with only marginal increases in NOx. The difficulty lies in adjusting the air flow into the intermediate zone properly at all power settings so it is hot enough for CO consumption, yet cold enough to prevent NOx, and still achieving flame stability, liner duability, etc.

4. Variable Geometry - Variable geometry provides control of the primary zone such that stable efficient combustion with minimum emissions occurs over the complete operating range of the engine. Air enters the combustor through holes equipped with a mechanism (usually a sliding ring) that meters the airflow in proportion to the fuel flow. With this system the primary zone fuel air ratio can be controlled to be stoichiometric at idle power for HC and CO reductions, and to be lean (but stable) at high power for NOx reductions.

Very limited testing with this type of combustor has been conducted and therefore not much data is available. The data does indicate that HC and CO can be reduced with the variable geometry combustor. However, the level of NOx increased slightly, owing to inadequate design.

This system has a number of operational drawbacks, primarily the reliability of the mechanical system in such a severe environment which is a safety issue. However, the notion of moving mechanical systems in severe environments is not new to gas turbines: variable pitch compressor stators and variable turbine nozzle guide waves do exist.

IV. Improvements in Combustor Operating Conditions

1. Increase in Idle Speed - As engine power is reduced, HC and CO levels generally increase as a result of lower temperatures and pressures at the combustor inlet. By increasing the engine speed at idle, therefore, the levels of HC and CO should be reduced. However, the level of NOx may increase because of the increased temperature in the combustor. The increased idle speed is limited on turbofan and turbojet engines by the capability of the aircraft brake systems as there is an increase in thrust. This problem does not exist with turboprop (class P2) engines as the thrust can be held nearly constant by properly varying the propellor pitch with engine speed. Also, there is an attendant increase in fuel consumption with increased engine speed.

2. Airbleed - The use of airbleed is merely a means of increasing the idle speed, particularly of a jet, without suffering the problems of increased thrust. The additional power is directed towards compressing and then dumping extra air instead of towards thrust. However, the use of airbleed results in increased fuel consumption which offsets some of the expected reductions in emissions.

3. Increased Combustor Length - Increasing the combustor length increases the residence time of the reactants. This technique theoretically reduces the levels of CO and HC by allowing the reactions to proceed further toward the goal of CO_2 and H_2O. NOx, however, might increase for the same reason. Results of testing this combustor technique indicate that the CO and HC levels decreased as expected.

A consideration in using this technique is that the length of the combustor casing would be increased, a major change in the engine which is likely to be reflected as a change in the engine length and/or center of gravity, both of which would affect engine installation.

4. Water Injection - Water injected into the primary zone of the combustor results in a lower primary zone temperature. Test results with water injection indicated that the lower primary zone temperature in turn results in a reduction in NOx as a result of the lower $N_2 \rightarrow NO$ reaction rate. However if the temperature is reduced too much, an increase in CO occurs.

The use of water injection presents many problems. The increased aircraft weight due to the mass of water carried may reduce the useful payload of the aircraft. (Usually, however, water injection results in increased thrust, and hence the payload can be increased). Higher fuel consumption is required to maintain turbine inlet temperatures. Precautions must be taken to prevent ice formation in the water injection system for operation at ambient temperatures below the freezing point of water. Water must be demineralized in order to prevent turbine blade corrosion and pitting. The use of tap water results in substantial turbine deterioration and thus compromises safety and engine reliability. (See Appendix C for results of the use of tap water). Demineralized water can be very expensive (over $0.30 per gallon) depending upon the location. Logistics for demineralized water may be a problem also, especially for those aircraft using smaller fields. This approach should be considered only if other techniques are unsuccessful in reducing emissions.

Section 5 - Summary of Best Demonstrated Control Methods

Based upon results of the engine related research programs discussed in Section 3, the best demonstrated combustor concepts have been listed in Table 5-I. The criterion used for selecting the best concept was to determine which came closest to meeting the three emissions levels and the smoke standard. In many cases the level of emissions was estimated from data supplied to the EPA by the manufacturers. It should be noted that the concepts listed for each engine may not be the best (in terms of reducing emissions) for that engine. The concepts listed are the best demonstrated concepts which were known at the time this report was written. As some of the data is nearly one year old, it is expected that further improvements have been made.

A comparison of the results in Table 5-I to the standards indicates that the NOx standard was achieved (without water injection) by only 33 percent of the engines listed. The CO and HC standards were achieved by 54 percent and 75 percent of the engines respectively. Therefore, it appears that the most significant unresolved problem is achieving the NOx standards without the use of water injection.

Table 5-I

Best Control Concept Demonstrated

Engine	Concept	Level Achieved			Category	Comments
		HC(EPAP)	CO(EPAP)	NOx(EPAP)		
Class T2 Standard		0.8	4.3	3		
CF6-50	Double annular (configuration D-13)	0.28	2.96	4.2	B	HC and CO are considerably under standard
	with water injection at takeoff.				A	
CFM56	Modified PV combustor with sector burning at idle	0.10	6.0	4.5	B	
CF6-6	Double annular.	Expected to be similar to D/A CF6-50				
	With water injection.			<3		
JT9D	Aerating nozzles with rich primary.	0.10	2.7	4.5	B	Has smoke number of 20
	With 7000 lb/hr water injection.			2.6	A	Has smoke number of 11
RB211	Airflow redistribution etc?	0.62	2.8	<3 with H_2O	A,B	
Class T3 Standard		0.8	4.3	3		
JT3D	Smokeless burner can.	18.0	26.2	5.6	B	
Class T4 Standard		0.8	4.3	3		
JT8D	Aerating nozzles with rich primary.	0.05	5.1	7.3	B	Has smoke number of 28
Class T1 Standard		1.6	9.4	3.4		
TFE731	Air assist (2.59 ppm).	0.4	6.0	5.2	B	Values estimated
	Estimated with water injection.			3.1	A	Water injection rate is equal to fuel flowrate.
ATF3	Reverse flow combustor.	5.8	16.9	4.1	B	Production combustor
CJ610	Reduced spray cone angle.	6.1	155	2.7	C	By redesigning fuel nozzles, HC is reduced 60%. Levels of NOx are acceptable. Further redesign is not practical.
CF700	Reduced spray cone angle.	3.8	94	2.2	C	
JT15D	Rich primary/delayed dilution & added swirl to nozzle air assist.	0.14	10.9	4.8	B	
M45H	Lean primary zone	1.2	8.3	3.4	A,B	
ALF502D	Airblast	12.0	4.2	1.9	B,C	
APU Class Standard		0.4	5	3		
GTCP85	Increase spray cone angle	0.07	3.7	6.2	B,C	Values estimated from production sampling.
GTCP30	Pressure atomizing fuel nozzles.	0.1	4.8	3.4	B,C	Values estimated. Horsepower based on η_c=.75 Production combustor.

Table 5-I continued

Engine	Concept	HC(EPAP)	CO(EPAP)	NOx(EPAP)	Category	Comments
GTPR36	Insufficient data to make estimate					
GTCP36	Airblast	0.09	7.7	5.4	B,C	AiResearch claims CO standard is achieved. Values estimated from rig test results and max. horsepower point in data.
TSCP700	Reverse flow combustor with simplex fuel nozzles	0.16	0.8	6.0	B	Production combustor
GTCP660	Straight through combustor with simplex fuel nozzles	0.20	7.9	4.9	B	Production combustor
ST6	Airflow redistribution	0.20	0.99	6.0	B	
Class P2 Standard		4.9	26.8	12.9		
TPE331	Reschedule fuel flow to operate only on primary atomizers at taxi-idle.	2.0	14.8	9.9	A,B,C	Best results were achieved at 65% rated speed and 5% rated power.
PT6A-27	Airflow redistribution.	6.2	21.9	8.5	B	
PT6A-41	Airflow redistribution.	1.8	16.6	8.3	A,B	
501D	Premix, airblast fuel nozzle, variable geometry.	1.6	4.0	6.1	A,B	
250	Premix combustor.	3.5	39.7	3.6	B	Values estimated
LTP101	Not known	30.5	5.1	6.5	B	

Definition
A - meets gaseous standard
B - best demonstrated
C - most cost effective

Section 6 - Summary of the Best Demonstrated Retrofitable Control Methods

One strategy available to the EPA to achieve a substantial reduction quickly in the contribution of aircraft to the urban air pollution load is through retrofit regulations wherein existing, in-use engines must be cleaned up by a certain deadline. Such regulations for smoke are already promulgated for the JT8D (T4 class) and JT3D (T3 class). The regulation is already in effect for the T4 class and will go into effect for the latter January 1, 1978, unless postponed in accordance with the notice of proposed rulemaking published by EPA on October 29, 1975 (Federal Register, Volume 40, Number 209, p. 50453). Another such regulation is pending for large (over 29,000 pounds-thrust) T2 class engines (Federal Register, Volume 38, Number 136, p. 19050, July 17, 1973). That proposed regulation would require all such in-use engines to comply by January 1, 1983 with the 1979 standards (HC, CO, NOx, and smoke) for T2 class newly manufactured engines.

The degree of success the manufacturers are having in attempting to comply with this future regulation, plus other potential retrofit situations not yet proposed, are summarized below in Table 6-I. These concepts do not require extensive combustor liner or engine case modifications and yet generally produce significant reductions in emissions. They are, therefore, quite cost effective as well as retrofitable. For five engines the best concept demonstrated is also the best retrofitable concept demonstrated. For the remaining four engines listed, however, the retrofitable concept demonstrated is not the best concept demonstrated, and thus represents a compromise in achieving low emissions. There were no retrofitable concepts demonstrated for fourteen of the engines which appear in Table 5-I and so they do not appear in the table here.

Table 6-1

Best Retrofitable Control Concept Demonstrated

Engine	Concept		Level Achieved		Category	Comments
		HC(EPAP)	CO(EPAP)	NOx(EPAP)		
Class T2						
Standard		.8	4.3	3		
CF6-50	Production combustor with 180° sector burning at idle	0.83	6.63	7.74	R	
CFM56	Production combustor with sector burning at idle	1.1	13.3	4.4	R	
JT9D	B/M burner with aerating nozzles	2.2	5.8	5.2	R	
Class T1						
Standard		1.6	9.4	3.7		
TFE731	20% airbleed at taxi-idle	1.9	15.3	4.3	R	Unattractive because of 14% increase in LTO fuel consumption.
CJ610	Reduced spray cone angle	5.1	155	2.7	R,B	
CF700	Reduced spray cone angle	3.8	94	2.2	R,B	
Class P2						
Standard		4.9	26.8	12.9		
TPE331	Reschedule fuel flow to operate only on primary atomizers at taxi-idle	2.03	14.8	9.90	R,A,B	Results were achieved at 65% rated power and 5% rated thrust.
APU Class						
Standard		.4	5	3		
GTCP85	Increase spray cone angle	0.066	2.6	6.2	R,B	
GTCP36	Airblast	0.04	5.4	7.7	R,B	Production combustor already has airblast air-assist nozzle.

Definition
R - retrofitable
A - meets gaseous emissions standards
B - best demonstrated

Section 7

Technology Comparison

I. There are two general areas of interest covered in this section. First, an examination of the trends of emissions as functions of certain engine parameters is presented. This will permit consideration of questions regarding the structure of the regulations, such as

(1) At what point do small engine characteristics (e.g., lower pressure ratios) dominate the emissions behavior?

(2) What is the nature of the emissions behavior of small engines?

(3) Is the CO/HC ratio of the standards technically reasonable?

These questions are being asked, but not answered, in this report. The presentation of the data should cast some light on these issues, however.

To investigate the first two questions, Figures 1 through 12 must be examined. Figures 1 and 2 show that there is no discernable relationship between the size of an engine and its combustion inefficiency at idle (the mode of the principal contribution to HC and CO emissions). This apparently contradicts the argument that the lower pressure ratios found in small engines (factual, see Figures 3 and 4) and the allegedly larger surface/volume ratios of the combustors of current small engines (questionable from Figures 5 and 6) contribute to the poorer emissions performance of small engines. The combustors of such engines evidently do perform as well as those of their larger counterparts insofar as combustion efficiency is concerned.

It is interesting to investigate the explicit effect of pressure ratio and surface/volume ratio on the combustor performance especially as the former is functionally related to the engine size (Figure 3). Figures 7 and 8 show that for all classes of engines, there is no clear, strong relationship between the combustion efficiency at idle and either the rated pressure ratio or the actual pressure ratio at idle. While it is accepted that changes in pressure affect the chemistry within a combustor, this lack of functional relationship among a population of engines shows that it is not the pressure ratio alone which determines the combustor idle emissions performance, but several factors such that if the pressure is adverse these other factors can be adjusted accordingly to achieve the desired result. These other factors include the air flow rate, the temperature, and the combustor volume. These, plus the pressure ratio, can be combined together into one semi-empirical parameter, the air loading parameter, which describes the condition of the combustor with regard to efficiency of combustion. It is, therefore, insufficient to consider engine emissions as dependent upon the pressure ratio. This will be discussed in detail later.

The surface to volume ratio, on the other hand, appears to show a correlation with the idle combustion efficiency (Figure 9). The trend, however, is hardly conclusive so the addition of data from the many engines for which surface/volume data is not available yet to EPA will be highly useful. As expected, this relationship shows those engines with higher S/V have, in general, a lower idling efficiency. However, as mentioned above, Figures 5 and 6 indicate no meaningful correlation between S/V and engine size, leading to the observation that S/V is not the basic reason for poor emissions performance in small (or large) engines.

By considering the whole engine and not simply the combustor performance, it can be seen that the lower pressure ratios (Figure 3) and, to a much less certain degree, the lower bypass ratios (Figure 10) of small T1 class engines lead to higher idle specific fuel consumptions (SFC) (Figure 11). The high SFC, especially at idle, of these small jet thrust engines is apparently the predominant cause for the higher EPAP values for HC and CO generally experienced by T1 engines in comparison with T2 engines. This can be seen more clearly in the following discussion.

The general trend of increasing values of the EPAPs for HC and CO for decreasing engine size is best seen by considering a weighted sum of the EPAPs for HC and CO, defined as

$$\Psi = .875\ \mathrm{EPAP(HC)} + 0.2322\ \mathrm{EPAP\ (CO)}.$$

As the vast bulk of the HC or CO emissions arise in the idle mode, then roughly, for instance,

$$\mathrm{EPAP\ (HC)} \simeq \mathrm{EI(HC)}_i \times M_f\ \mathrm{(idle)}/I$$

where EI_i = emissions index at idle (lbs of pollutant per 1000 lbs of fuel), M_f = mass of fuel consumed during the mode in question, and I = total impulse of the engine over the cycle. It then follows that

$$\Psi = [.875\ \mathrm{EI(HC)}_i + 0.2322\ \mathrm{EI(CO)}_i] \times M_f\ \mathrm{(idle)}/I$$

The bracketed term is merely the combustion inefficiency $(1 - \eta_c)^*$ times 1000 at idle. The second part, M_f (idle)/I is proportional to the idle SFC, for

$$\frac{M_f\ \mathrm{(idle)}}{I} = \frac{M_f\ \mathrm{(idle)}}{I_{idle}} \times \frac{I_{idle}}{I}$$

$$= \mathrm{SFC}_{idle} \times \frac{I_{idle}}{I}$$

where the ratio of the idle impulse to the total cycle impulse is roughly a constant, varying slightly with the manufacturers recommended power setting for idle. Ψ then is basically proportional to $(1 - \eta_c) \times$ SFC at idle.

Figure 12 shows how Ψ (a weighted sum of the EPAPs for HC and CO) increases with decreasing engine size. As Ψ is proportional to $(1 - \eta_c)$ x SFC and as it has been seen already that $(1 - \eta_c)$ is not related to engine size (Figure 1), then obviously the EPAP behavior can be explained only by the increasing idle SFC with smaller engines (Figure 11), as claimed above.

While it is historically true that smaller jet thrust engines have suffered higher SFCs than their larger counterparts, certain data points on Figure 11 suggest that the most modern of the T1 engines are achieving SFCs approaching those of the larger modern engines. If that is the trend in the future, then it would seem that there is no technical basis for a distinction between the T1 and T2 classes. The only argument that would favor the retention of a separate T1 class is that the technology necessary for the T2 class engines to meet their standards is in some way impractical or perhaps even impossible to incorporate into small engines. This argument must be assessed carefully, for if it cannot be substantiated, there may be little need for a separate T1 class.

In comparison, the existence of the P2 class seems to be justified because; first, the primary output is power, not thrust, and so normalization of the cycle pollutants is based on energy (power x time) rather than impulse (thrust x time) as is the case of the jet thrust type engines (T1 through T4 classes); second, their excellent SFC characteristics would support as technically feasible a separate, more stringent standard; and third, their capability to operate at higher engine speeds at idle (more favorable conditions for combustion efficiency and hence low HC and CO emissions) than jet thrust engines because of their ability to feather the propellor would make compliance with stronger standards more likely. Despite all this, it can't be said with certainty that the P2 class standards are more or less stringent than those for jet thrust engines for standards with different dimensions (energy vs. impulse) cannot be readily compared. An obvious possibility, of course, is to determine the static thrust of a turboprop (P2) engine and propellor combination, thereby permitting a standardization of the dimensions among all propulsion classes; pollutants from turboprops would be presented with respect to impulse instead of energy so that the P2 class standards could follow the same format as the jet thrust classes.

Question 3 can be considered in the light of Figures 13 through 17. Figure 13 shows the relation between the EPAPs for HC and CO for production engines. Superimposed on the graph are the various standards with which these engines will have to comply by 1979. While the T2 class is grouped in such a way that there is not a good trend line to allow extrapolation the P2 and T1 class show good trend lines permitting extrapolation.

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*The weighting factor 0.875 is prefixed onto the $EI(HC)_i$ because the hydrocarbon emissions index is based on methane (CH_4) whereas the fuel itself has a hydrogen-carbon ratio of about 2.

Ideally for the designer, the trend line would cross the appropriate standards "box" at the upper right hand corner. From the Figure, it appears that for the two classes for which trend lines are established this criterion is approximately satisfied. The HC/CO ratio required by the standards would seem to be reasonable.

Figure 14 shows the actual combustor HC/CO performance (at idle). There does not appear to be the difference here between the P2 and T1 classes; in fact all combustors appear to have the same general behavior. This would suggest that the difference between the EPAP ratios of HC to CO for the T1 and P2 classes that appears in Figure 13 is due to a difference in the combustor behaviors of the two classes at some power setting other than idle, presumably approach. This has, as yet, not been investigated in detail.

Figure 15 also shows the combustor HC/CO performance at idle, but now for the advanced combustors which have been developed in attempts to comply with the EPA aircraft emissions standards. There is considerably more scatter with these combustors which reflects the increasing diversity of combustor design.

It is instructive to consider how the HC/CO ratio (or here, the reciprocal $\beta = EI(CO)/EI(HC)$) in the combustor varies with the degree of combustor inefficiency (Figures 16 and 17). Figure 16 examines production type combustors, while Figure 17 examines advanced combustors. There is one notable point to be made here. It is that a few engines show a counter trend towards a lower β as the inefficiency decreases (Figure 17). While predominantly P2 class engines, one in this counter trend is a T2 class engine. A consistent pattern of either combustor design or engine operating mode has not yet been identified to explain this. This phenomenon cannot be seen in Figure 15 as well (at the lower values of combustion inefficiency) because that curve will be directed towards the origin for decreasing inefficiency for any and all values of β, thus obscuring major differences in β.

II. The second general area of interest is that of demonstrated or potential improvements in combustor emissions performance. In general, compliance with the EPA standards can be achieved by either improvements in the combustor emissions performance (lower emissions indices) or improvements in the fuel consumption characteristics (see Appendix B). However, as compliance with the 1979 standards for newly manufactured engines generally applies to engines that are already in existence, there is little that can be done to effect significant improvements in the fuel economy short of the development of a new engine. This leaves only improvements in the combustor emissions performance as a means to comply the 1979 standards. Thus, a review of the combustor development work is especially important.

Consideration of the emissions will be divided into (1) HC and CO phenomena and (2) NOx phenomena. To the extent that there is a design tradeoff between CO and NOx, there will be some overlap.

HC and CO emissions arise from incomplete combustion, primarily at idle and, to a lesser degree, approach. The extent of incomplete combustion can be measured quantitatively through the combustion inefficiency,

$$1-\eta_c = .875 * EI(HC) + .2322 * EI(CO) \times 10^{-3}$$

where EI denotes the emission index. The factor .875 is included in the hydrocarbon term since the EI is expressed in terms of methane (CH_4) whereas the fuel is closer to CH_2, the ratio of the molecular weights being 0.875.

Incomplete combustion results from;

(1) poor fuel preparation (atomization and distribution),

(2) conditions adverse to the evaporation and ignition of the droplets (low inlet temperature),

(3) inadequate residence time of the flow in the combustor for completion of the reactions (particularly $CO \rightarrow CO_2$ which is quite slow).

These effects can be described collectively in a single semi-empirical parameter, the air loading parameter, Ω:

$$\Omega = \frac{\dot{M}}{P_3^{1.8}\ V\ f(T_3)}$$

where

$$f(T_3) = \exp\ (T_3/540)$$

The terms in this expression are:

$\dot{M}a$ = combustor air mass flow rate (lb/sec)

P_3 = combustor inlet pressure (atmospheres)

V = combustor liner volume (ft^3)

T_3 = combustor inlet temperature (°R)

The expression represents a rough approximation of the extent to which the fuel combustion should have proceeded. Specifically,

$$\Omega \sim \frac{1}{\text{(reaction rate)} \times \text{(residence time)}}$$

Thus, larger values of Ω mean that the product of the rate times the time is small, indicating that either the reaction rate or the residence time or both are small and that, in any case, the reaction cannot have proceeded very far before the fuel exits the combustor. High values of combustion inefficiency would then be expected. On the other side of the coin, smaller values of Ω indicate that the reaction should have proceeded quite far before the fuel, what is left of it, exits. Low values of combustion inefficiency would be expected.

A combustor, for any given engine will experience a range of Ωs depending upon the power level of the engine, higher power means lower Ω. The actual range of Ω from the high power setting to the low will vary between engines and is dependent upon such design variables as the compressor pressure ratio, the size of the combustor, and the idle power setting level. A combustor that is run in a rig test at a simulated power setting will experience a different Ω for that power than in an actual engine, unless all the inlet conditions are faithfully reproduced. In any event, the characteristic emissions curve of $1 - \eta_c$ vs Ω will be generated.

The level of emissions control technology for HC and CO emissions which are the products of incomplete combustion can then be investigated systematically by comparing the combustion inefficiency of different control concepts at equal values of the air loading parameter.

Figures 18, 19, and 20 show the relationship between the air loading parameter and the combustion inefficiency for the four principal turbine classes. Classes T3 and T4 are included within the T2 class and APUs are included within the P2 class. Within each class a definite correlation is seen between Ω and $1-\eta_c$. There is some scatter, however, which is systematic, with specific engine lines falling above or below the curve. It may be inferred in such cases that those engines whose characteristic air loading parameter vs. combustion inefficiency lines fall above the mean curve are poorer than average in their emissions performance (HC and CO).

It should be emphasized, though, that insofar as HC and CO emissions are concerned, it is primarily the idle mode (high Ω) that is crucial (because of the relative emission rates and times in mode at the various powers). Therefore, the peculiar behavior of the CFM56 at high power in which its combustion inefficiency does not drop as rapidly as might be expected is not particularly important as far as HC and CO control is concerned.

The motivation behind the design of an emissions control scheme is to lower the characteristic $1-\eta_c$ vs. Ω curve of a given engine, primarily at low power as explained above. The extent to which that line must be lowered depends upon the fuel economy of the engine, primarily at the low power modes because the dependence of the EPA parameter on both the emissions index and the specific fuel consumption (Appendix B). For example, the Pratt and Whitney JT9D and the General Electric CF6-50, which are similar with respect to fuel economy, must achieve an idle combustion inefficiency of about 0.012 (excluding production margins) in order to meet the HC and CO standards (assuming also that the HC/CO ratio is correct). This is indicated on Figure 18. Because of the larger air loading parameter of the CF6-50 at idle, the task is more difficult, however. Also noteworthy is the excellent combustor HC and CO emissions performance of the JT8D with its new smokeless can. Unfortunately, its higher SFC implies a very low combustion inefficiency is necessary in order to meet the standards.

It is instructive to compare the average trend lines of the different classes. On Figure 20 is superimposed the trends of the T1 and T2 classes onto the P2 and APU trend. It is evident that the different classes follow different trends indicating that each class has reached a different level of combustor emissions performance. It must be emphasized, though, that none of these production combustors have been designed particularly for low emissions. Other, often conflicting, performance goals have dictated the design. It is notable, through, that the T1 class has, in its production engines, the most advanced combustors in use from the emissions point of view. Actual HC and CO emissions levels are not better than for the larger T2 class engines, but the performance is achieved under very adverse conditions of high air loading parameter.

Figure 20 also points out that the APU class engines, even those of low rated pressure ratio (GTCP85, GTCP660), have HC and CO emissions performance comparable to the other classes.

Figures 21, 22, and 23 show the combustion inefficiency performance of the best demonstrated combustors for the various engines. As these tests were usually run in rigs, not in the engines, the test conditions and hence, the air loading parameters, were usually not at the engine values. Nonetheless, the air loading parameter concept permits comparison between the advanced combustors and the production ones. Superimposed on each curve are both the trend lines of the production average and the advanced average for comparison. It is evident that progress has been made.

A comparison of the advanced combustor trend lines shows that, like the production engines, the T1 class achieves, as a whole, better HC and CO emissions performance than the other classes. It has only been the design selection of the combustors (volume) that has led to the very large air loading parameters at idle and the resulting mediocre combustion inefficiency. Increasing the combustor volume to lower the air loading parameter is not usually a practical fix for an existing design as it is likely to lead to changes in the casing of the engine. Such a change will increase the residence time in the combustor to help the combustion of HC and CO; however, this increased residence at high power will likely lead to additional NOx production.

Both the T1 and T2 classes (including T3 and T4) have apparently implemented designs which are effective in reducing the combustion inefficiency at all power levels as the advanced technology trend lines are low and parallel to those of the respective production trends. For the P2 and APU classes, on the other hand, the combustion inefficiency has been noticeably reduced only at the larger air loading values. While this is acceptable in general for the turboprop (P2) engines which, because of their excellent specific fuel consumption, are close to or within compliance limits anyway, it offers little help to the APU class which is tested only at high power (small air loading value) at which little improvement in the combustion inefficiency has been demonstrated. The reasons behind this lack of improvement at high power for the P2 and APU classes in comparison to the other classes has not yet been explored in detail.

The emissions performance of a combustor for the oxides of nitrogen can be evaluated directly by the plot of the emissions index vs. the combustor inlet temperature (equivalent to the compressor discharge temperature and, therefore, related to the compressor pressure ratio, which is an alternative but equivalent presentation). Figures 24, 25, and 26 present the baseline NOx performance curves for production engines of the various classes, including APUs. Unlike the emissions performance for the products of incomplete combustion (HC and CO), all classes follow the same curve, referred to generally as the Lipfert correlation. Figure 27 summarizes the preceeding three to demonstrate this. The correlation is a straight line on a semilog plot indicating, therefore, that

$$EI(NOx) \propto e^{\frac{T}{T_o}}$$

where here T_o is 258 °R.

The next series of curves, Figures 28, 29, 30, and 31 presents the NOx emissions performance of the best demonstrated combustors. There are far fewer data points with which to project accurate trend lines; however, some observations can be made.

First, in Figure 28, it appears that fuel staging (CF6-50) is superior as a NOx control technique than simple improvements to existing systems as evidenced by the other two engines which utilize a modified air flow pattern to obtain a rich primary plus an aerating or air blast type nozzle. This is reasonable as the temperature distribution within a fuel staged combustor can be better controlled at each power setting to minimize NOx production without compromising the low CO qualities too much.

Of course, this number of data points is hardly adequate to draw definitive conclusions. Further, the preculiar bucket shape of the CF6-50 profile may be due to erroneous data or due to the flexibility inherent in the fuel staging concept (to reduce CO at approach, the staging is set to have a fairly rich, hot primary zone to encourage the $CO \rightarrow CO_2$ reaction which has the unfortunate consequence of increasing the NO production also). A third possibility is that the Lipfert correlation concept (EI(NOx) vs. T_3) is inadequate to describe combustor rig data wherein the high pressures of the high power points cannot, in general, be simulated. This would affect the NO reaction rate as well as the residence time. This possibility will be investigated in detail prior to the final report.

Figure 29 compares the NOx performance of T2 class production combustors (Figure 24) with that of the few advanced combustors (Figure 28).

Figure 30 suggests, with what data is available, that there has been no improvement in the NOx emissions characteristics of T1 class engines, and in fact, a slight degradation in performance is possible at low powers. However, the data base is totally inadequate to draw conclusions: (1) the CF700 already meets the NOx standard so there is no motivation to improve upon it; (2) the only other two sets of data points are related concepts applied to the same engine. Substantially more data is necessary before conclusions can be made. No data for the TFE 731 is presented as the best demonstrated control technique (all pollutants) does not involve any modification to the combustor or injector, but only the application of compressor air bleed at idle. This is interesting, though, in that at idle it reduces the emissions rate of all three pollutants.

Figure 31 appears to repeat for the P2 and APU classes the situation found for the T1 class. Again both the turboprops and the APU behave in a similar manner and no NOx improvement has been demonstrated. But, as all P2 engines meet the relevant NOx standard, there is no motivation for improvement. In fact, in a number of cases, the designers in their efforts to reduce the HC and CO emissions are willing to increase the NOx emissions as a tradeoff. The APU engines, on the other hand, all fail to comply with the NOx standard, including the ST6 which as a P2 class engine (PT6A) meets the P2 standard. It appears that the APUs will have to develop an as yet unidentified method for NOx control which exceeds the requirements of the P2 class.

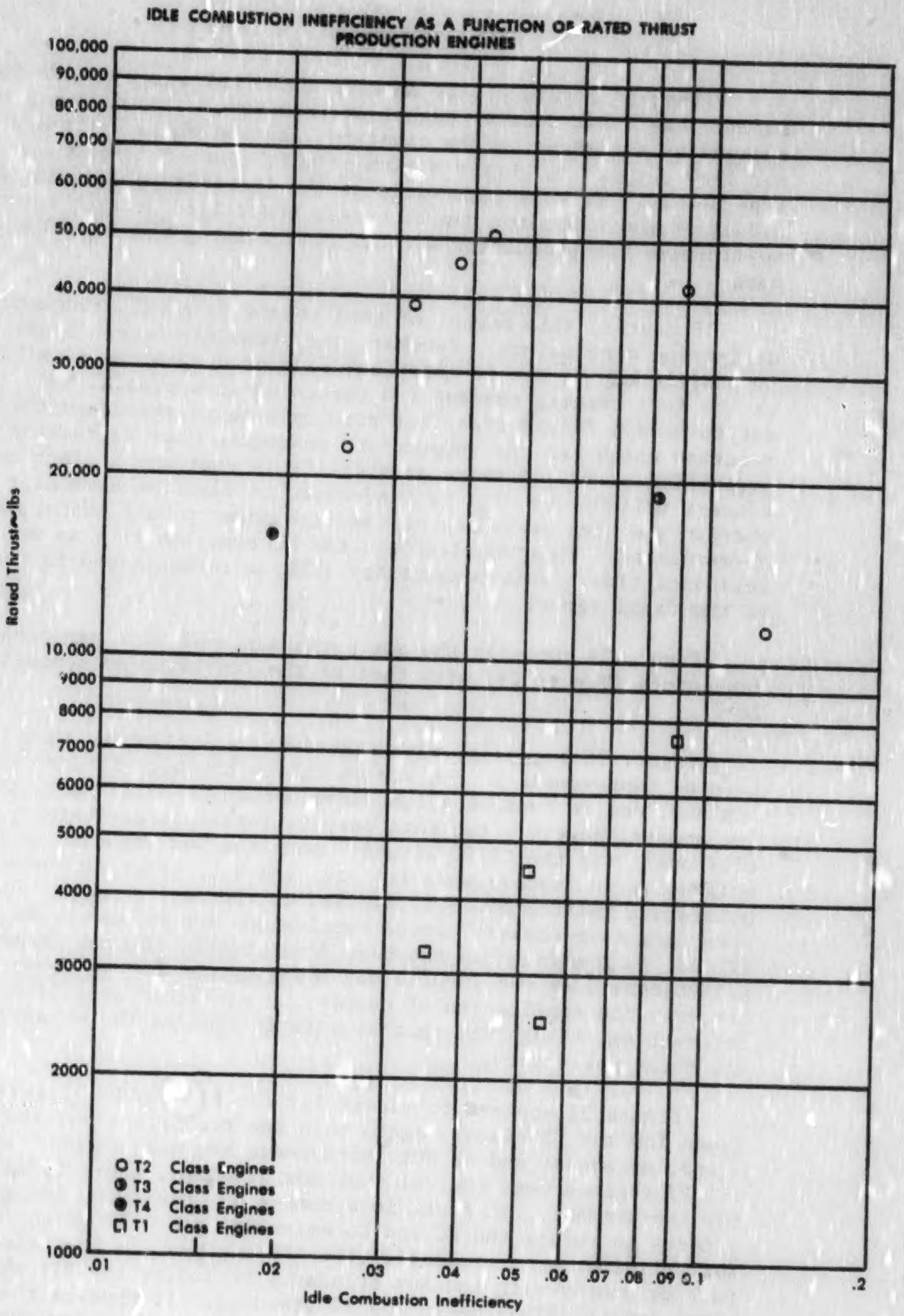

IDLE COMBUSTION INEFFICIENCY AS A FUNCTION OF RATED THRUST
PRODUCTION ENGINES
Rated Thrust~lbs
100,000
90,000
80,000
70,000
60,000
50,000
40,000
30,000
20,000
10,000
9000
8000
7000
6000
5000
4000
3000
2000
1000
.01
.02
.03
.04
.05
.06
.07
.08
.09
0.1
.2
Idle Combustion Inefficiency
○ T2 Class Engines
◉ T3 Class Engines
● T4 Class Engines
☐ T1 Class Engines

Figure 1

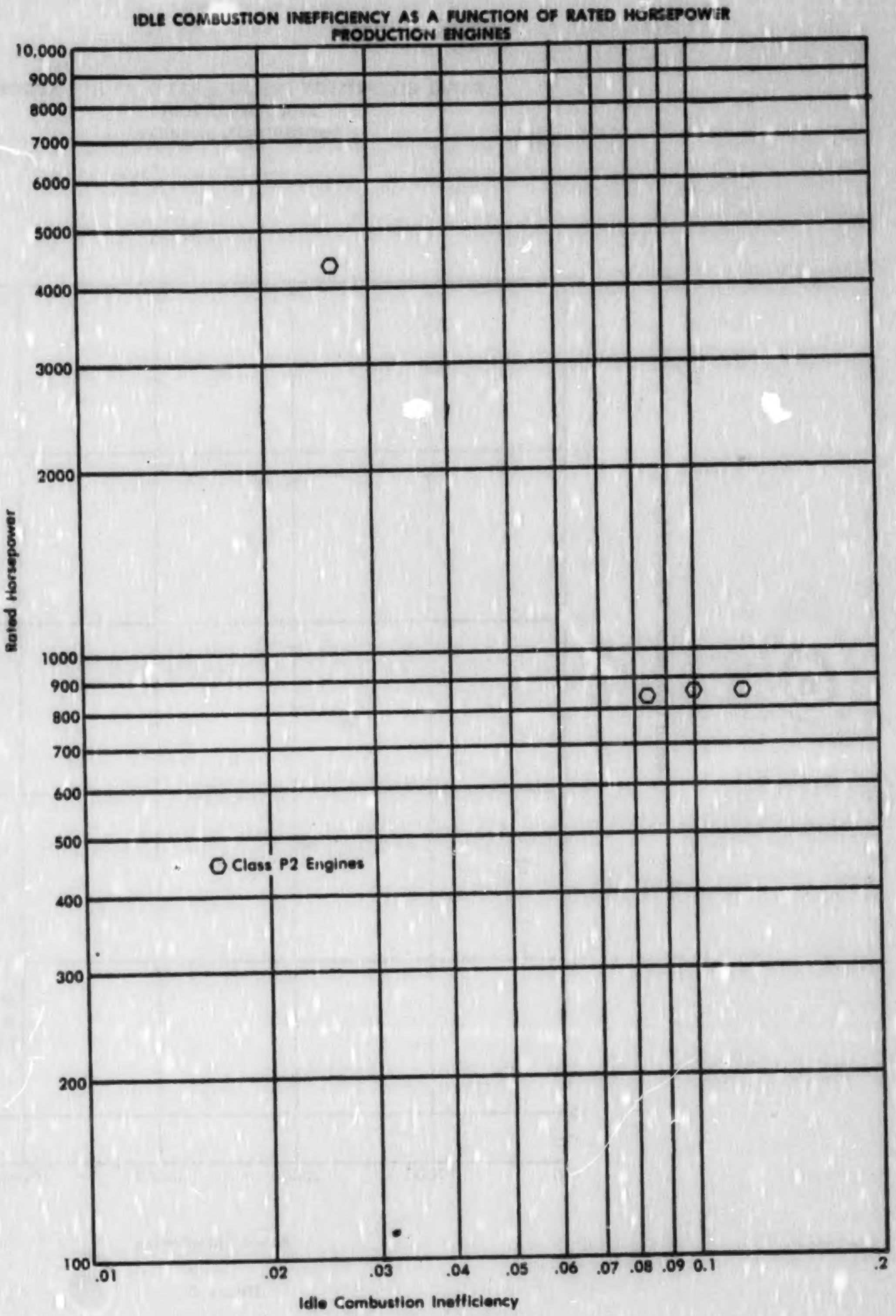

IDLE COMBUSTION INEFFICIENCY AS A FUNCTION OF RATED HORSEPOWER
PRODUCTION ENGINES

Figure 2

RATED COMPRESSOR PRESSURE RATIO AS A FUNCTION OF RATED THRUST PRODUCTION ENGINES

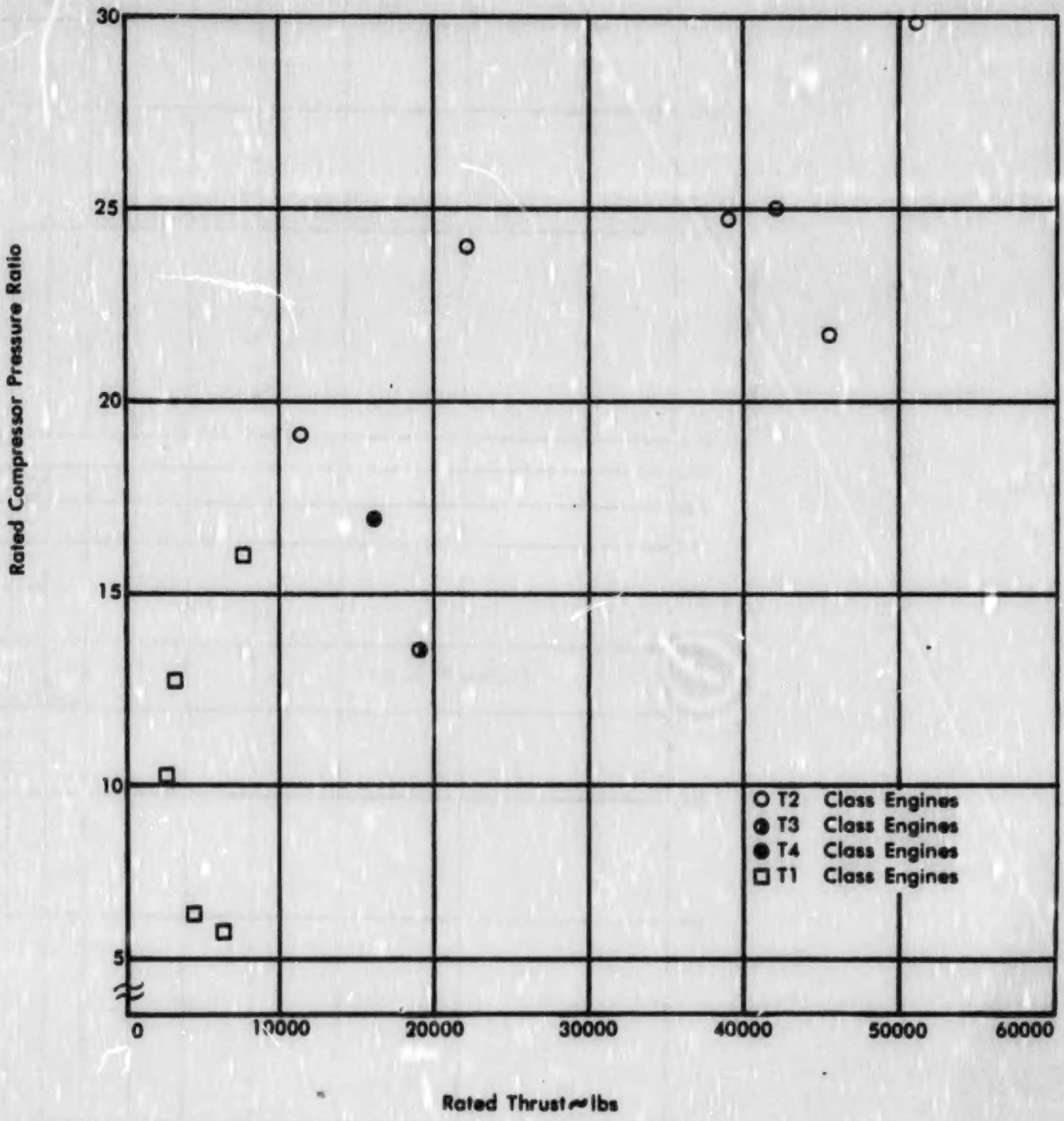
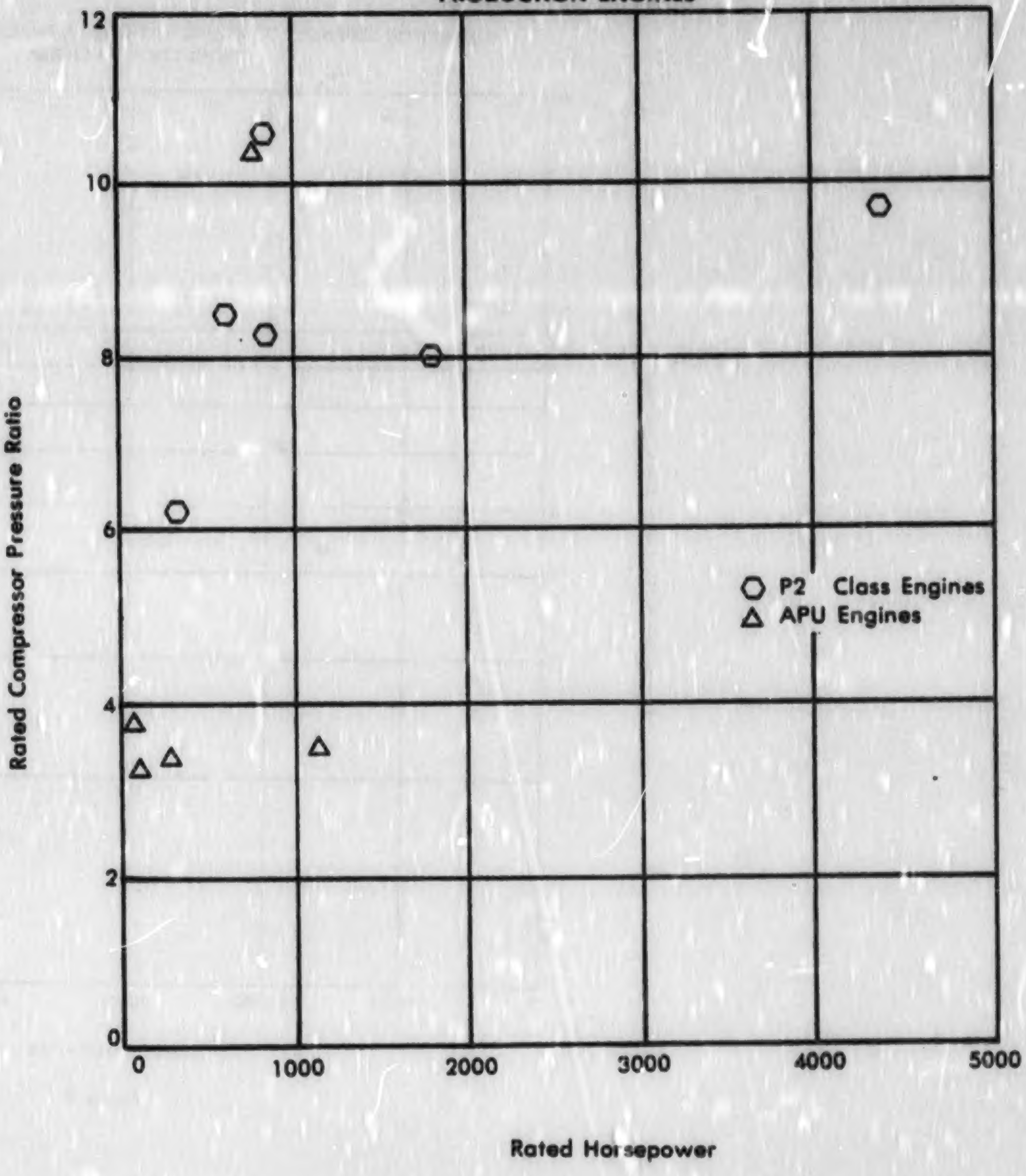


Figure 3



RATED COMPRESSOR PRESSURE RATIO AS A FUNCTION OF RATED HORSEPOWER PRODUCTION ENGINES

Figure 4

COMBUSTOR SURFACE TO VOLUME RATIO AS A FUNCTION OF RATED THRUST
PRODUCTION ENGINES

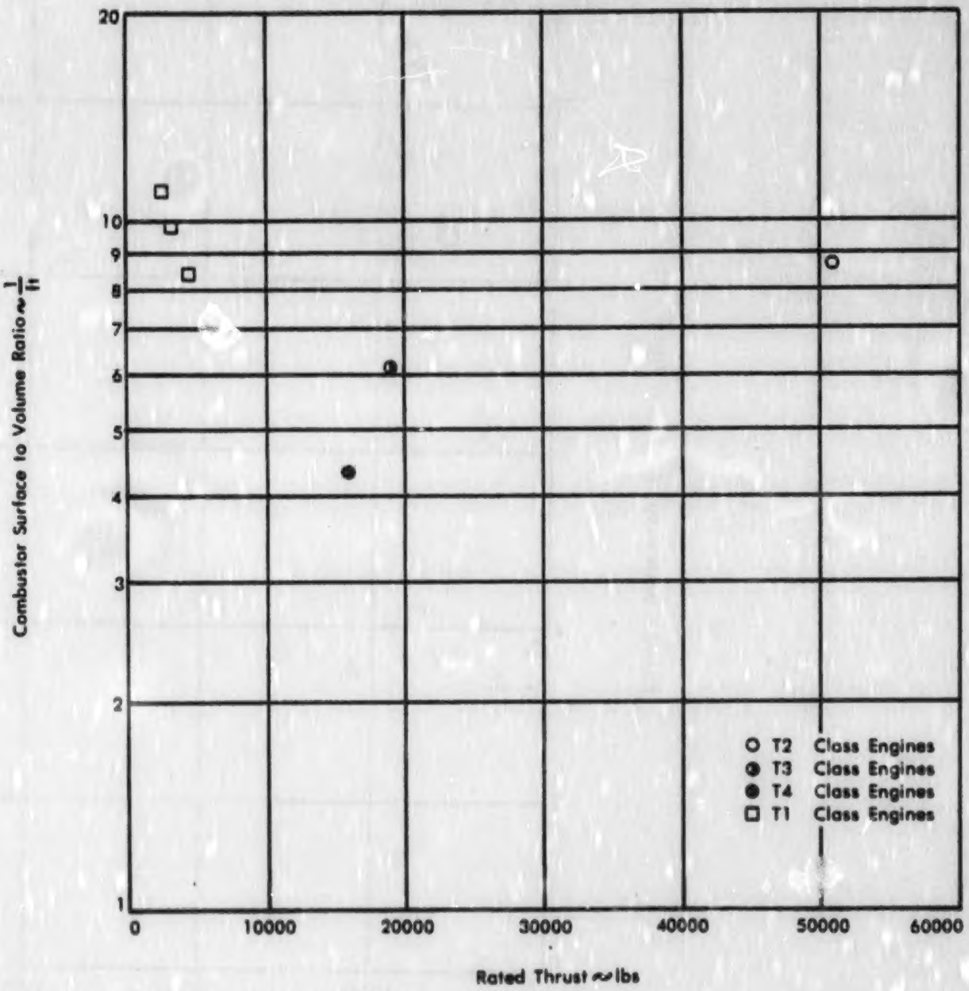


Figure 5

COMBUSTOR SURFACE TO VOLUME RATIO AS A FUNCTION OF RATED HORSEPOWER PRODUCTION ENGINES

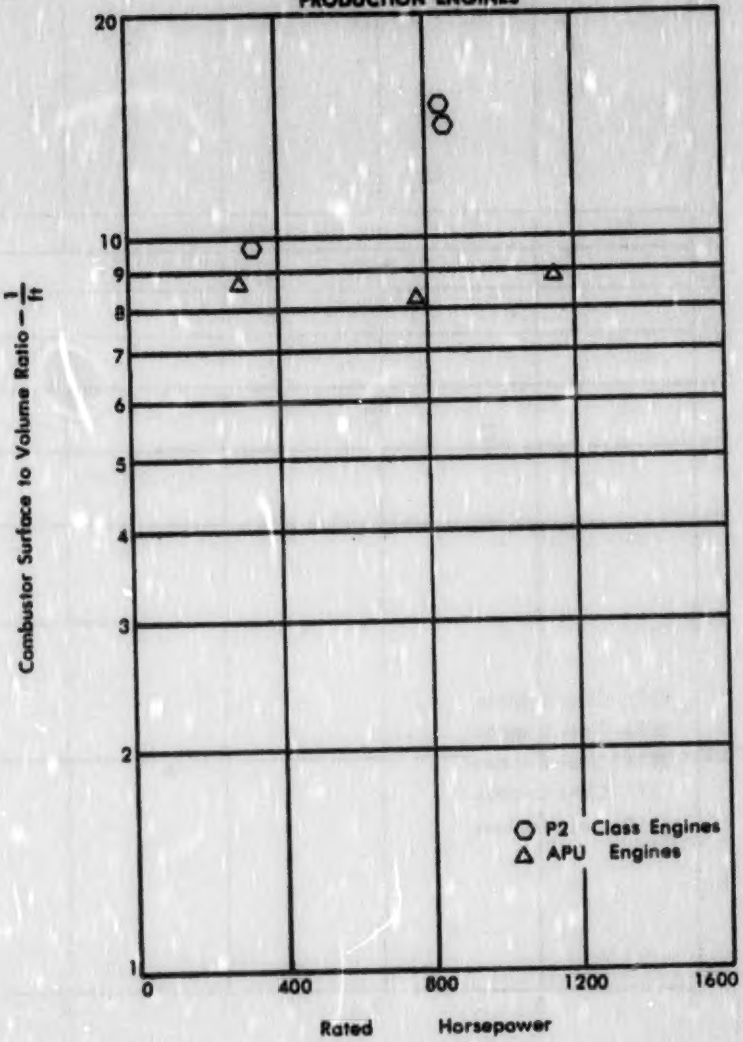


Figure 6

IDLE COMBUSTION INEFFICIENCY AS A FUNCTION OF RATED COMPRESSOR PRESSURE RATIO PRODUCTION ENGINES

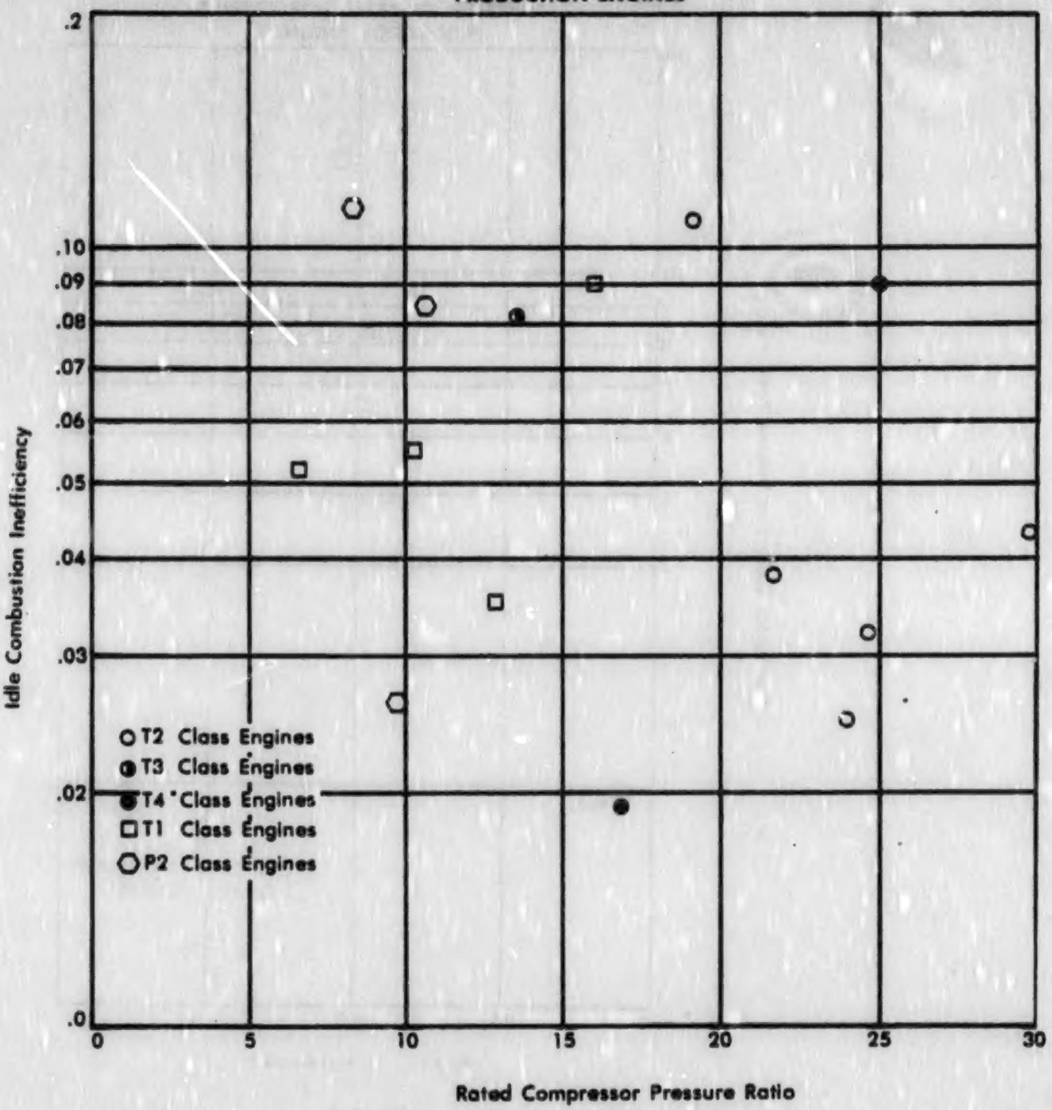


Figure 7

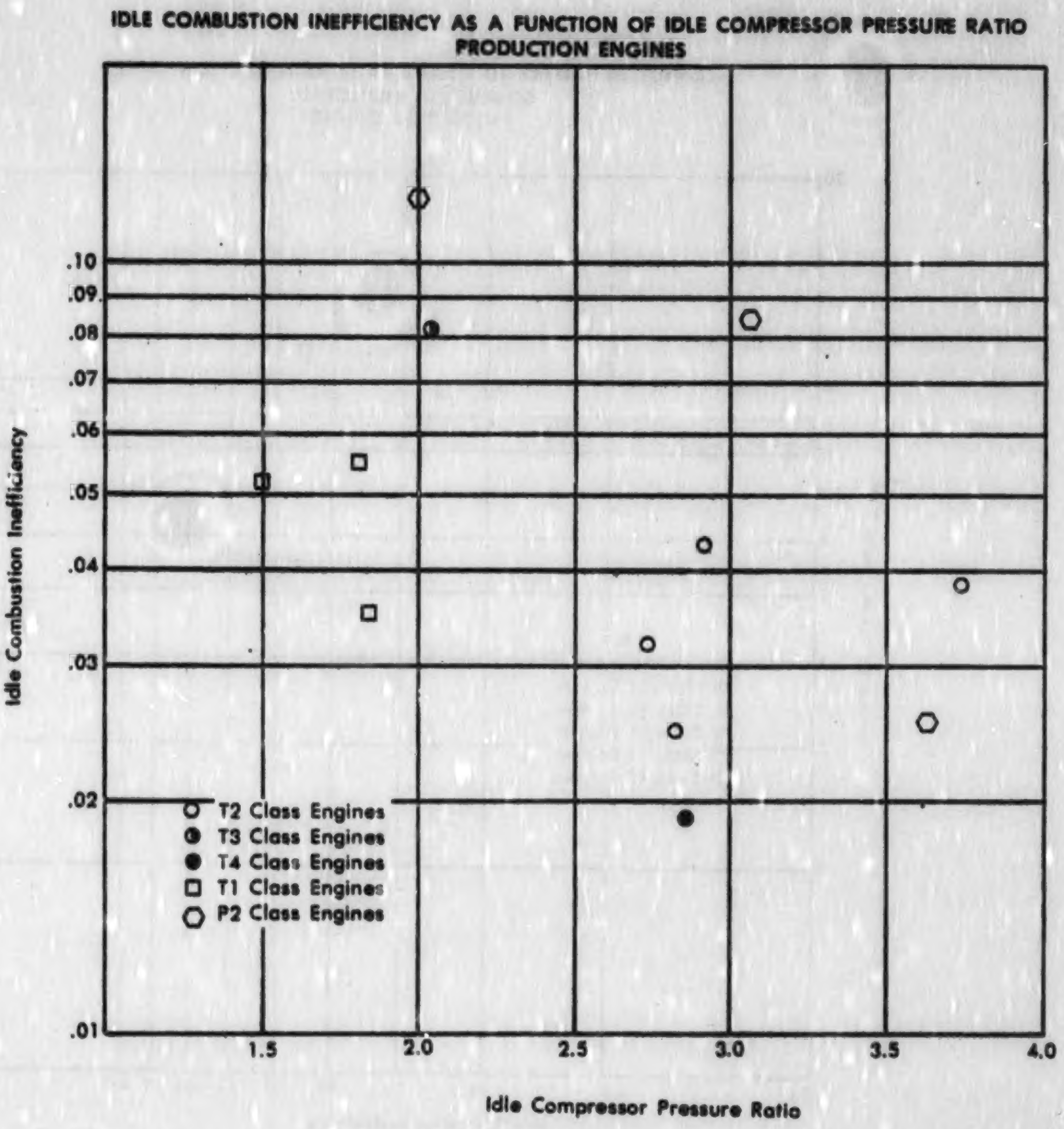

IDLE COMBUSTION INEFFICIENCY AS A FUNCTION OF IDLE COMPRESSOR PRESSURE RATIO
PRODUCTION ENGINES

Figure 8

COMBUSTOR SURFACE TO VOLUME RATIO AS A FUNCTION OF IDLE
COMBUSTION INEFFICIENCY
PRODUCTION ENGINES

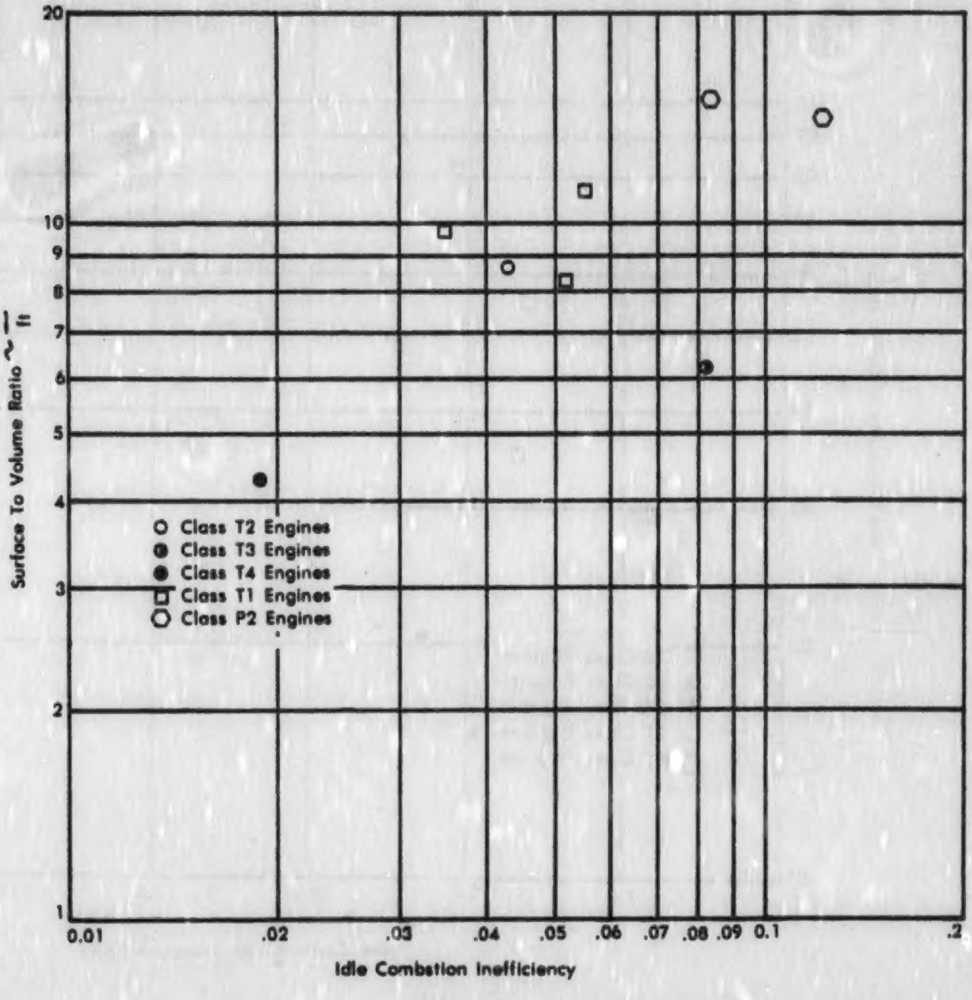
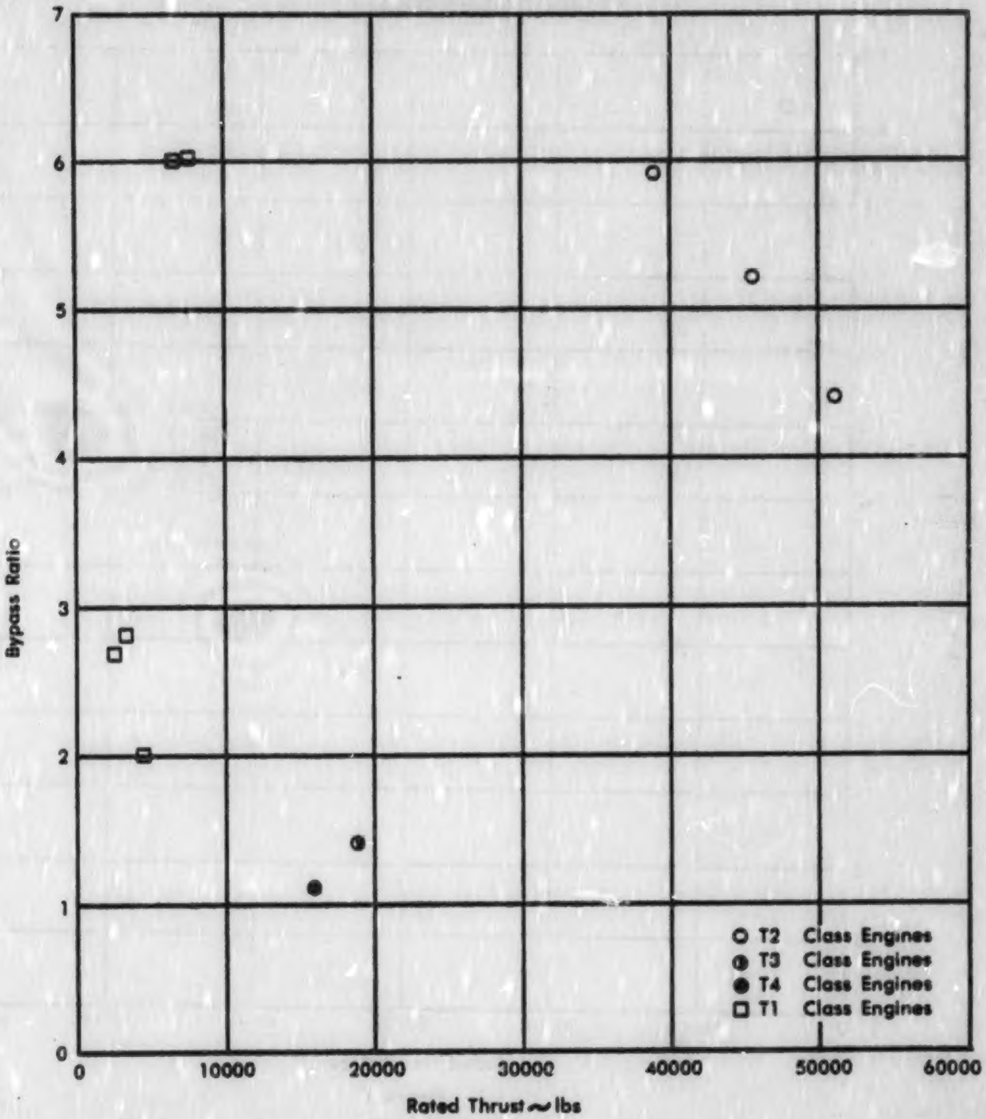


Figure 9



BYPASS RATIO AS A FUNCTION OF RATED THRUST
PRODUCTION ENGINES

Figure 10

IDLE TSFC AS A FUNCTION OF RATED THRUST
PRODUCTION ENGINES

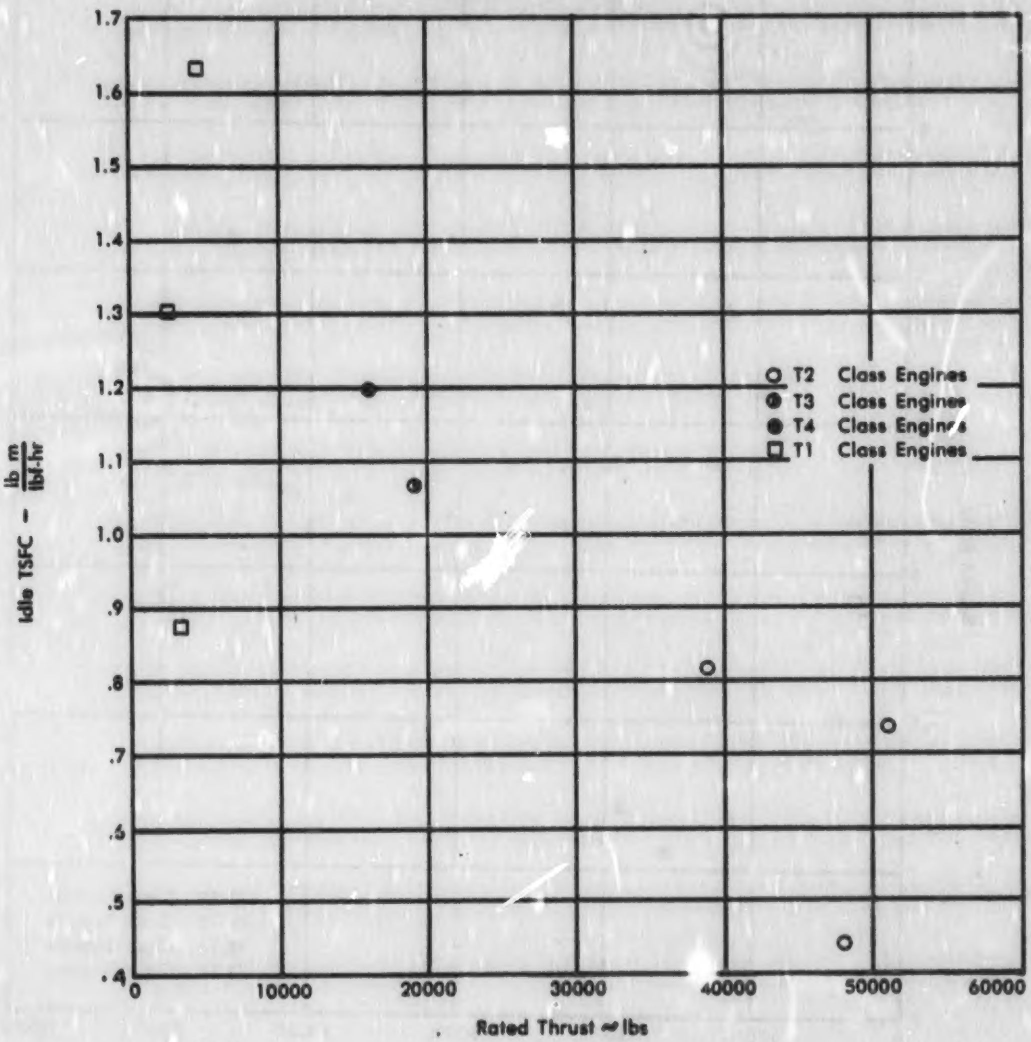


Figure 11

ψ AS A FUNCTION OF RATED THRUST
PRODUCTION ENGINES

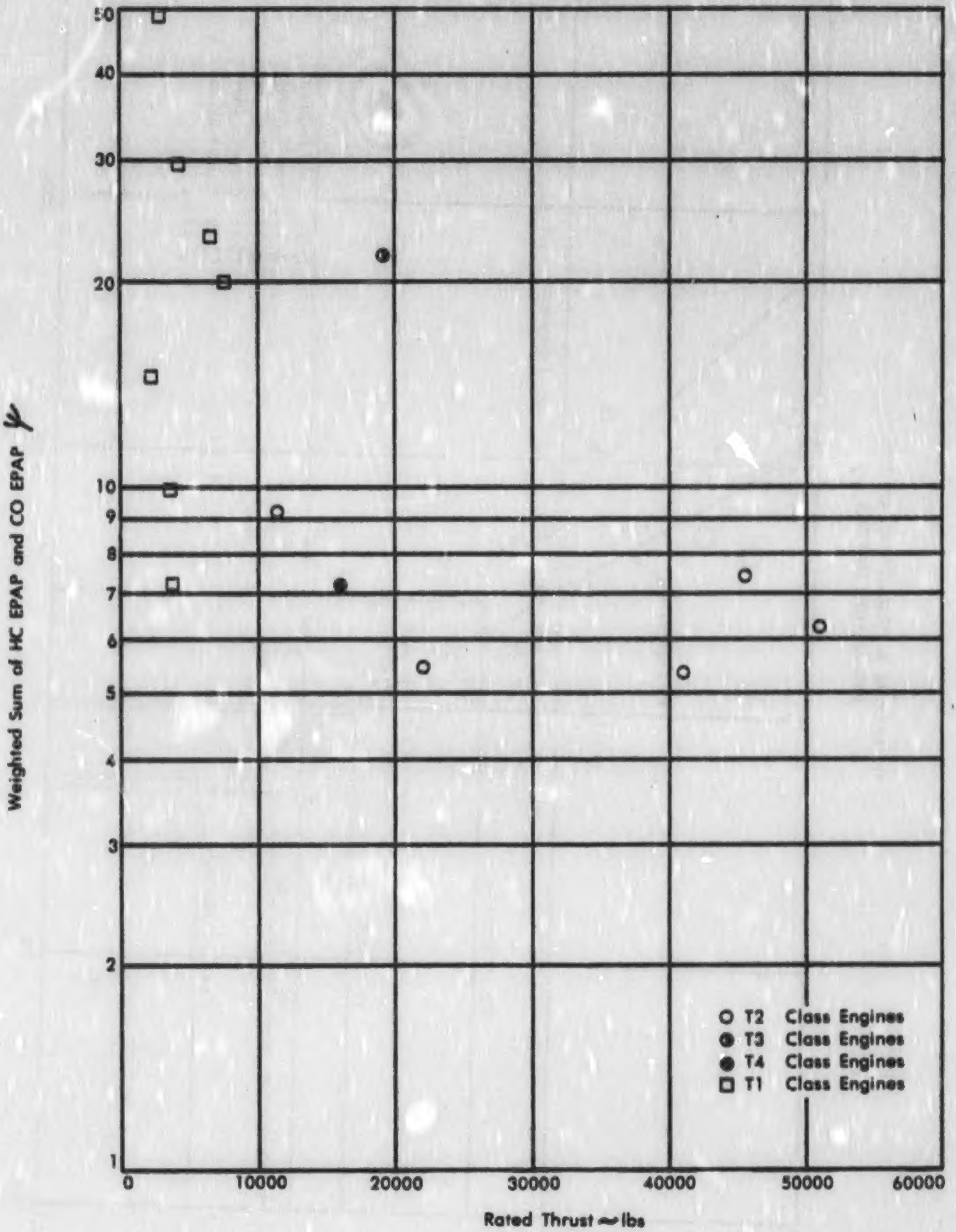


Figure 12

HC EPAP AS A FUNCTION OF CO EPAP
PRODUCTION ENGINES

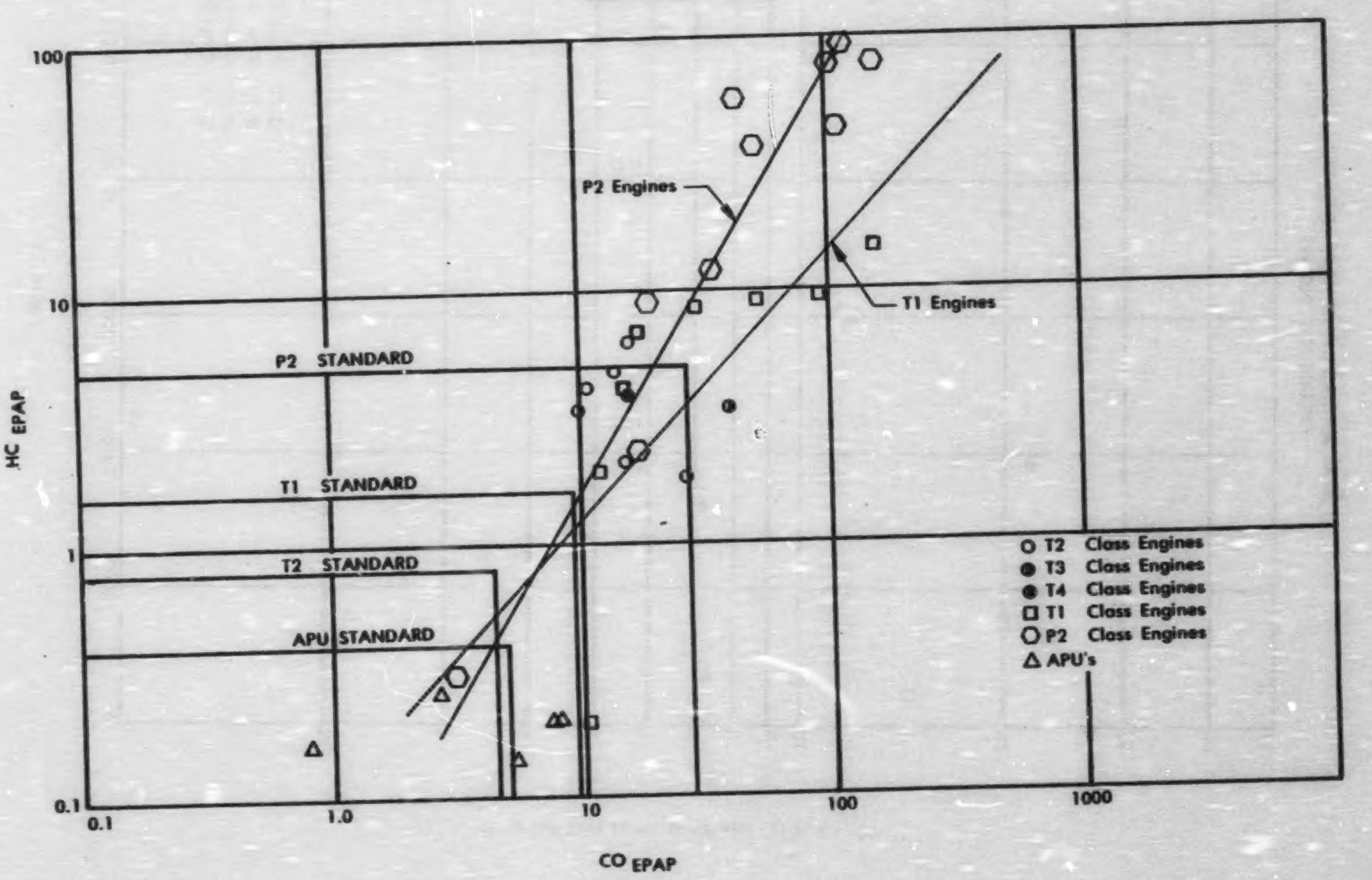


Figure 13

IDLE CO EMISSIONS INDEX AS A FUNCTION OF IDLE HC EMISSIONS INDEX PRODUCTION ENGINES

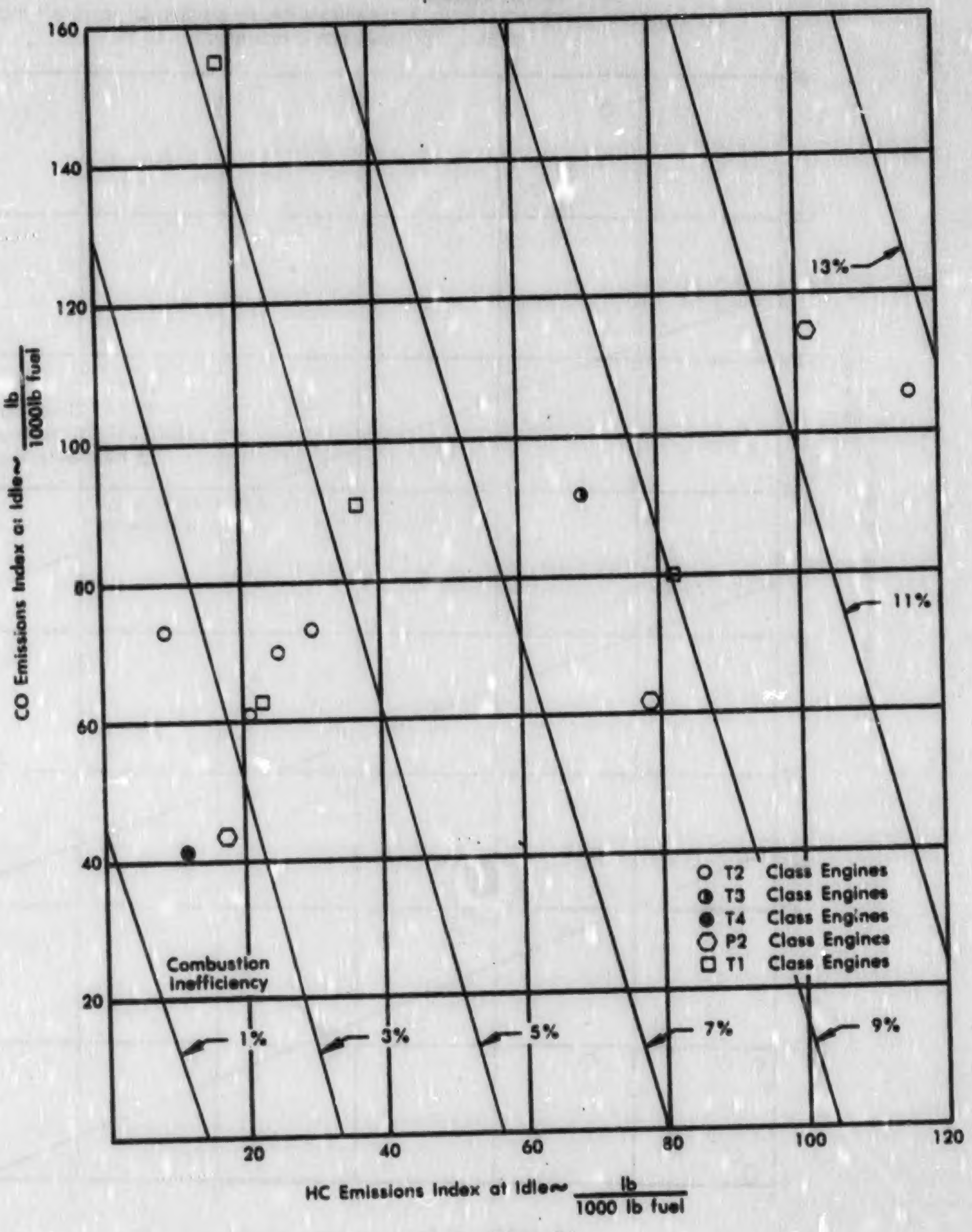


Figure 14

CO EMISSION INDEX AT IDLE AS A FUNCTION OF HC EMISSIONS INDEX AT IDLE
ADVANCED COMBUSTOR CONCEPTS

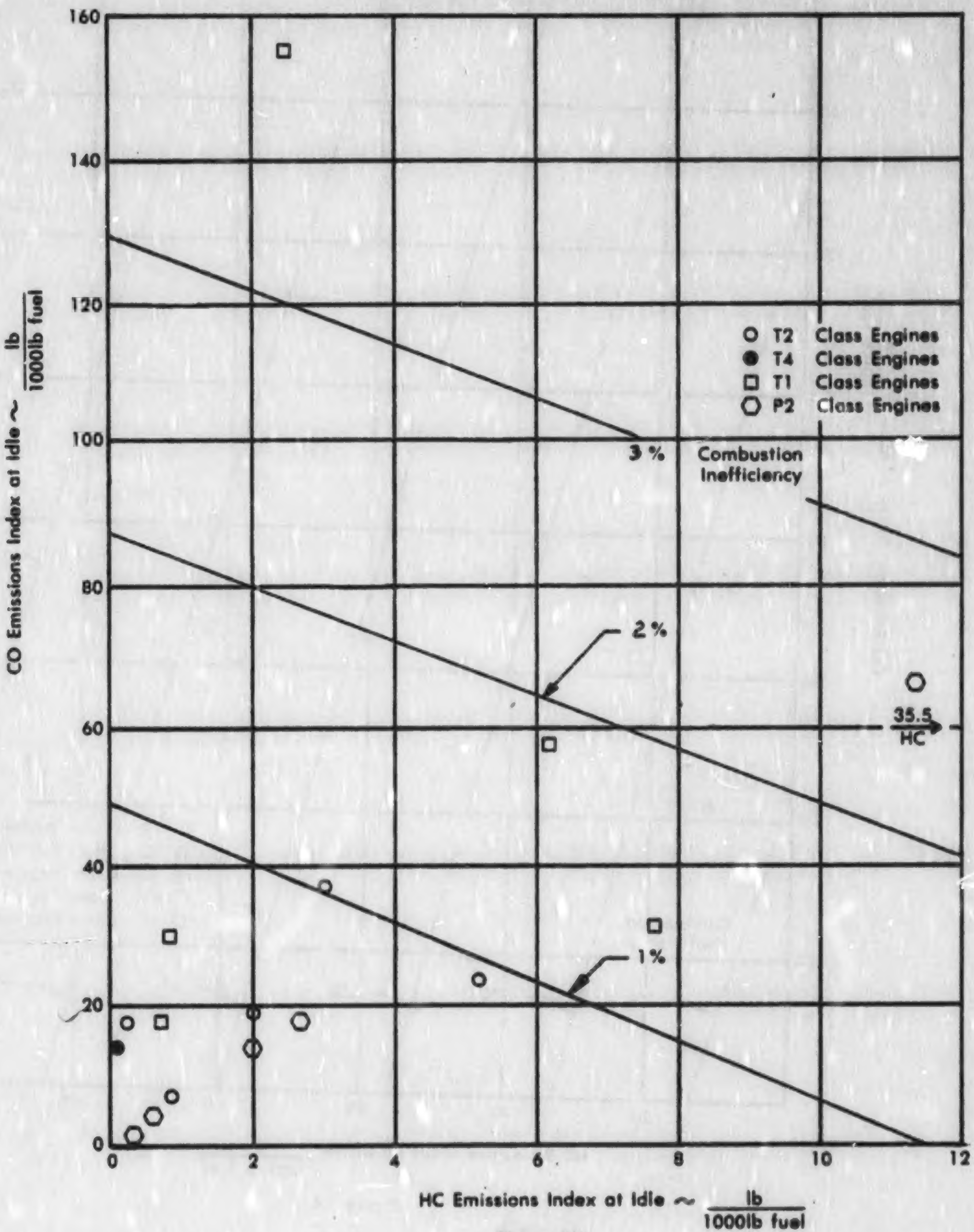


Figure 15

IDLE $\frac{EI_{co}}{EI_{hc}}$ AS A FUNCTION OF IDLE COMBUSTION INEFFICIENCY
PRODUCTION ENGINES

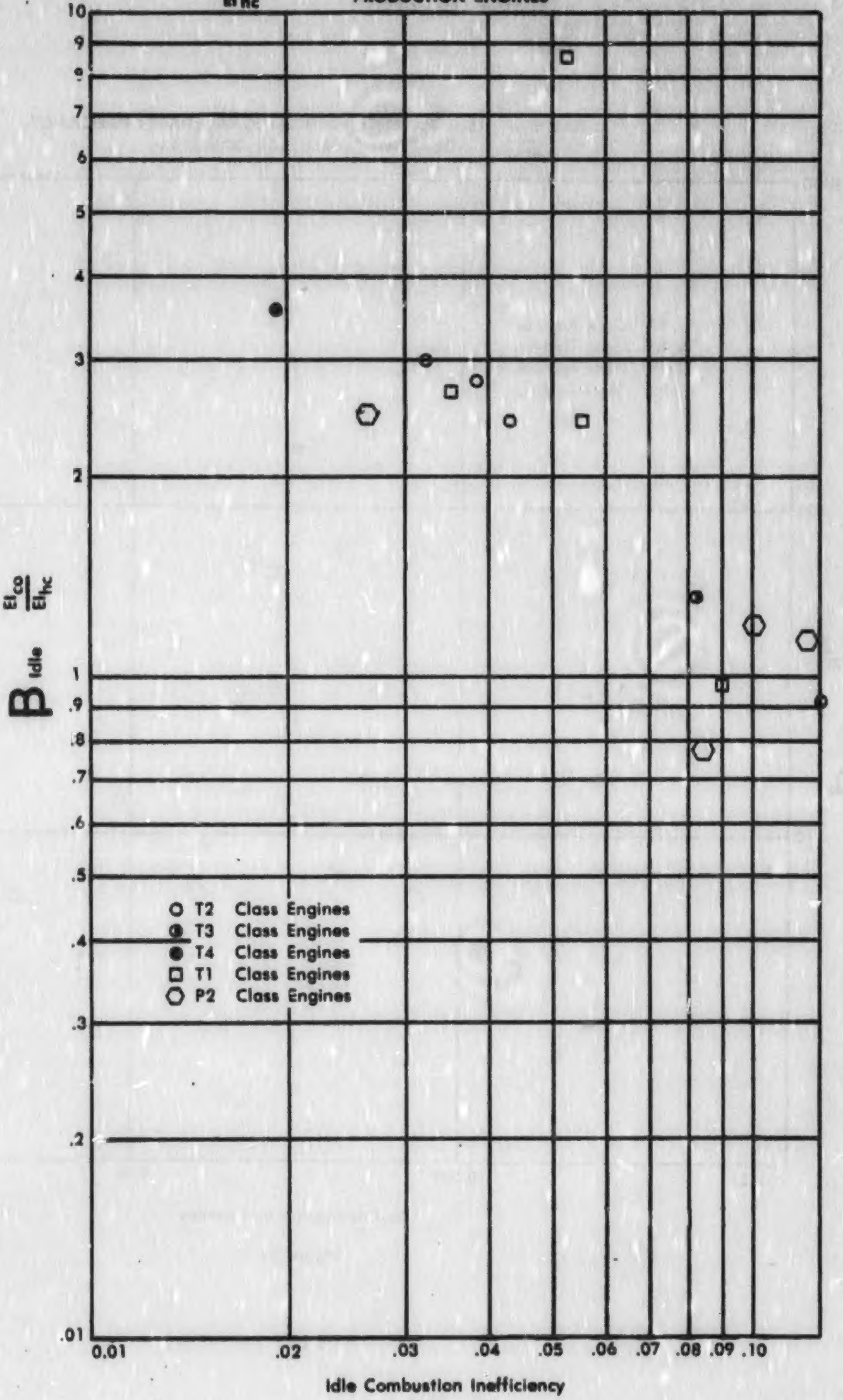
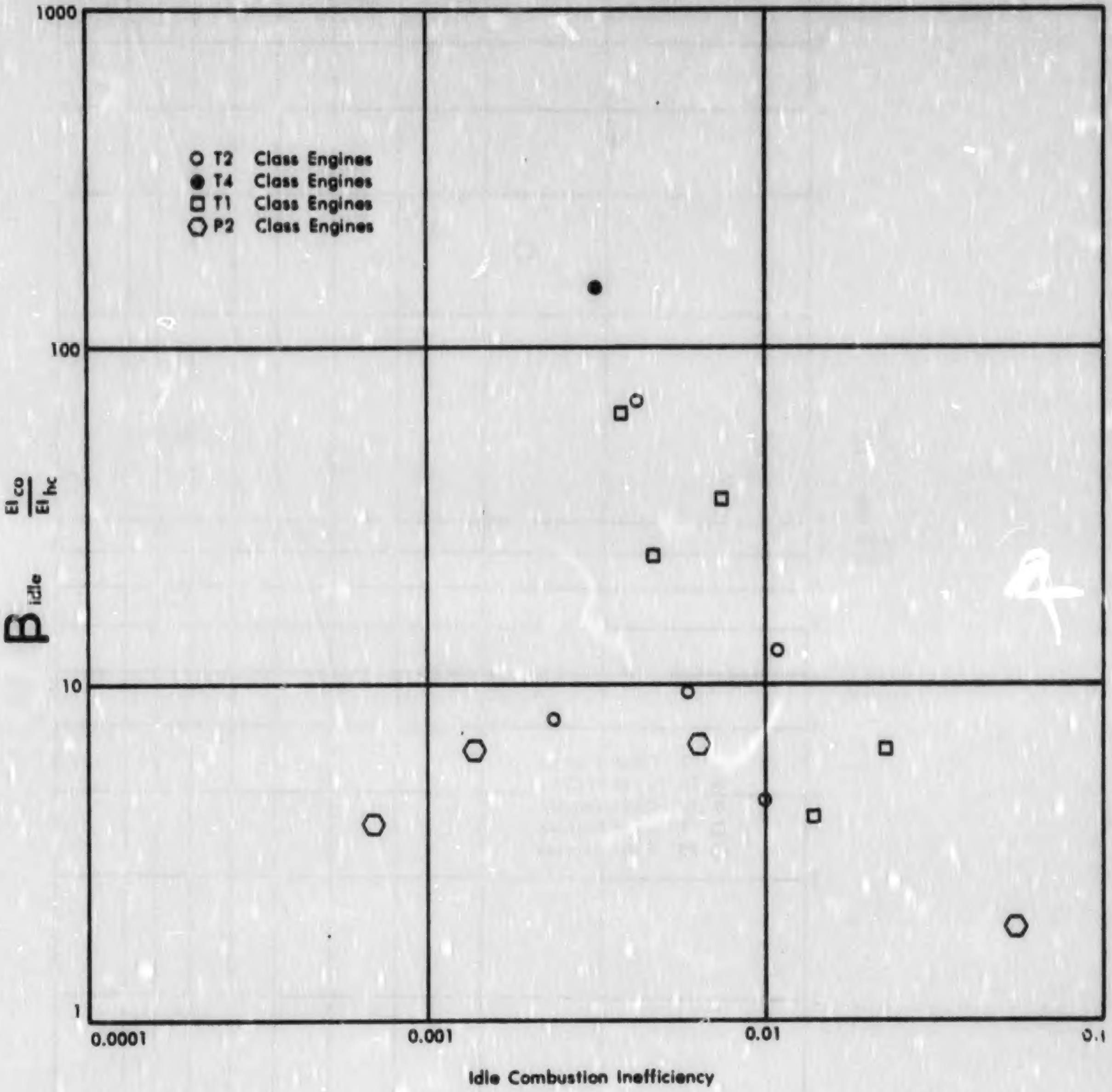


Figure 16

IDLE $\frac{EI_{co}}{EI_{hc}}$ AS A FUNCTION OF IDLE COMBUSTION INEFFICIENCY
ADVANCED COMBUSTOR CONCEPTS



4

Figure 17

COMBUSTION INEFFICIENCY AS A FUNCTION OF AIR LOADING PARAMETER
PRODUCTION ENGINES
CLASS T2

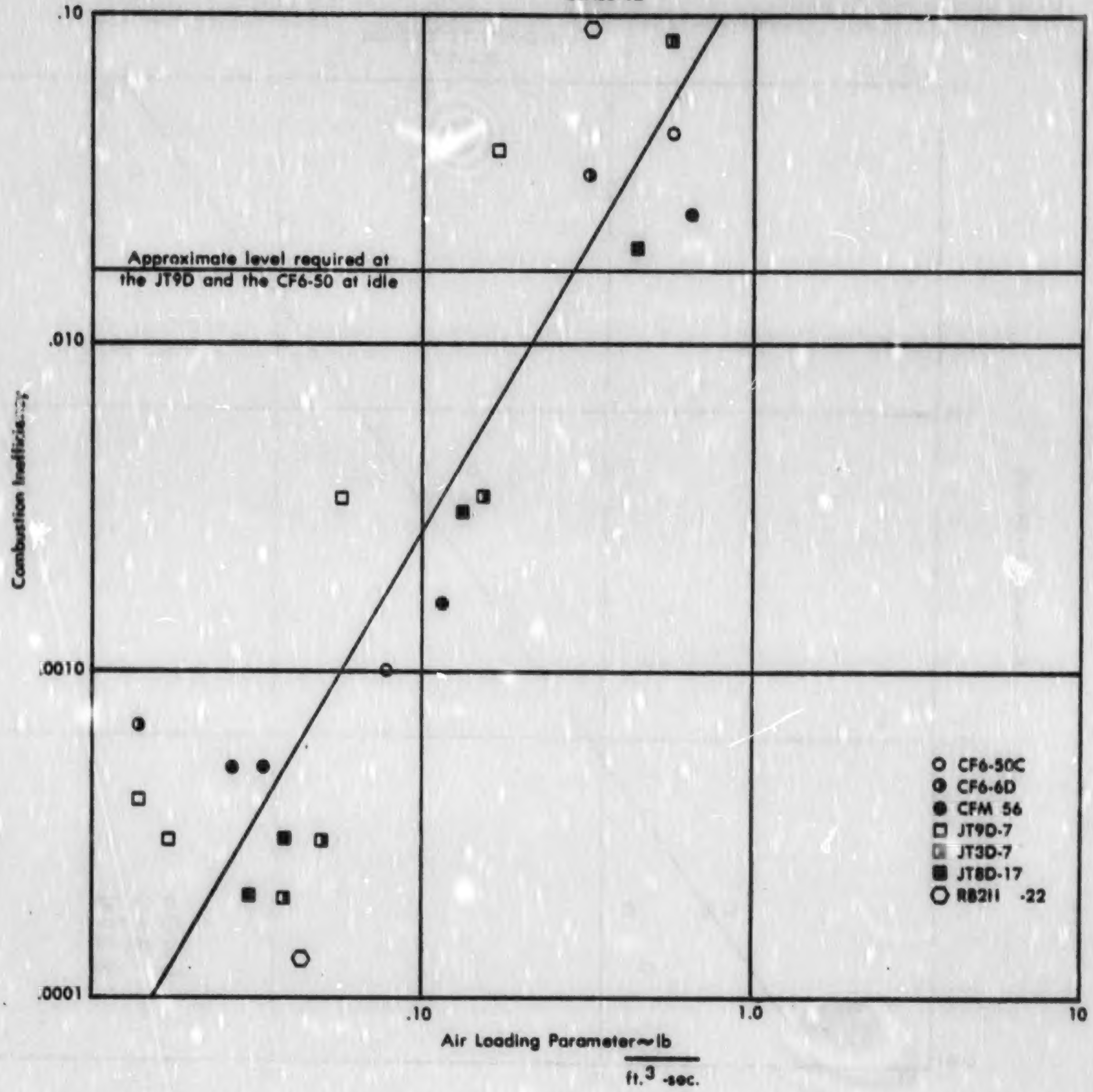


Figure 18

COMBUSTION INEFFICIENCY AS A FUNCTION OF AIR LOADING PARAMETER
PRODUCTION ENGINES
CLASS T1

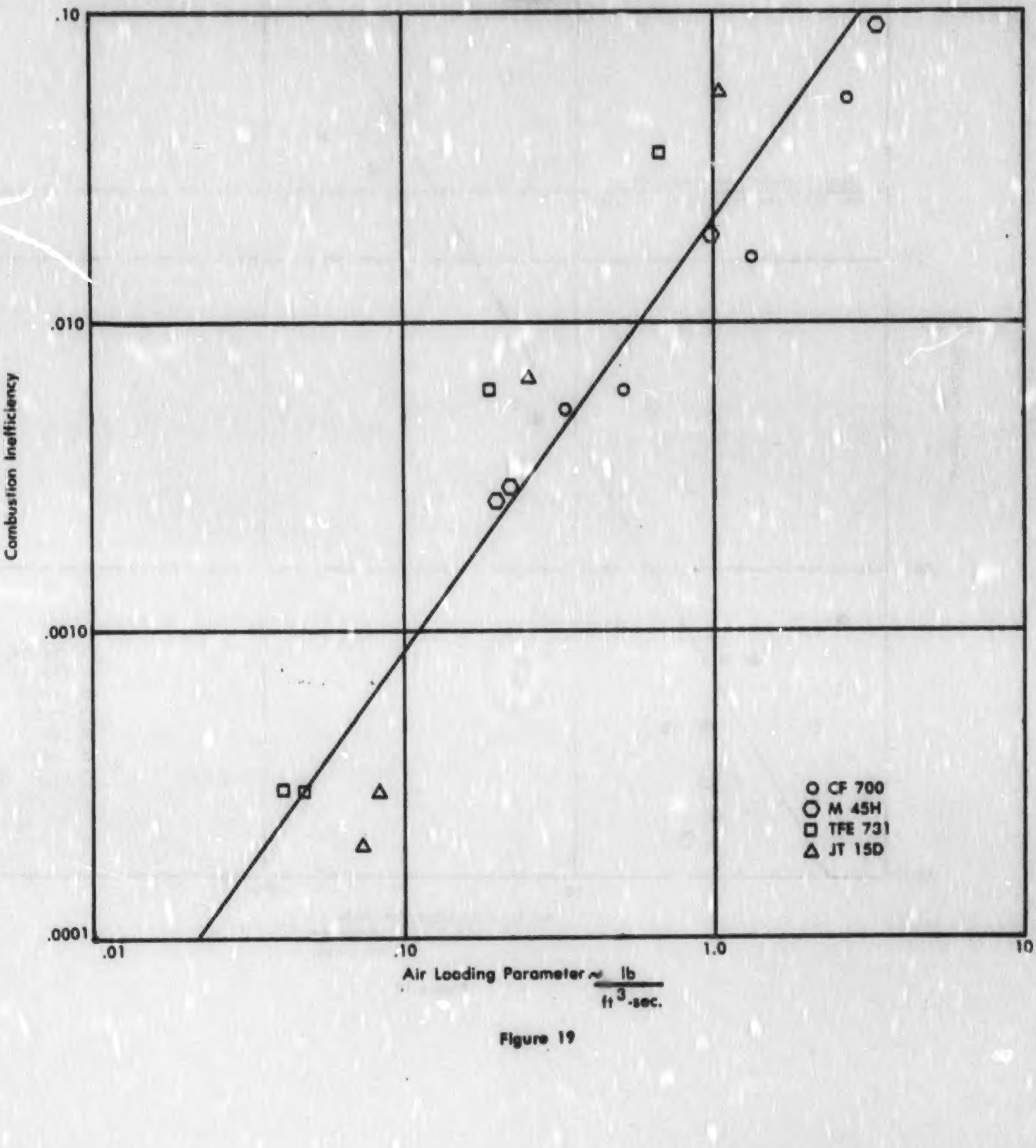


Figure 19

COMBUSTION INEFFICIENCY AS A FUNCTION OF AIR LOADING PARAMETER
PRODUCTION ENGINES
CLASS P2 AND APU's

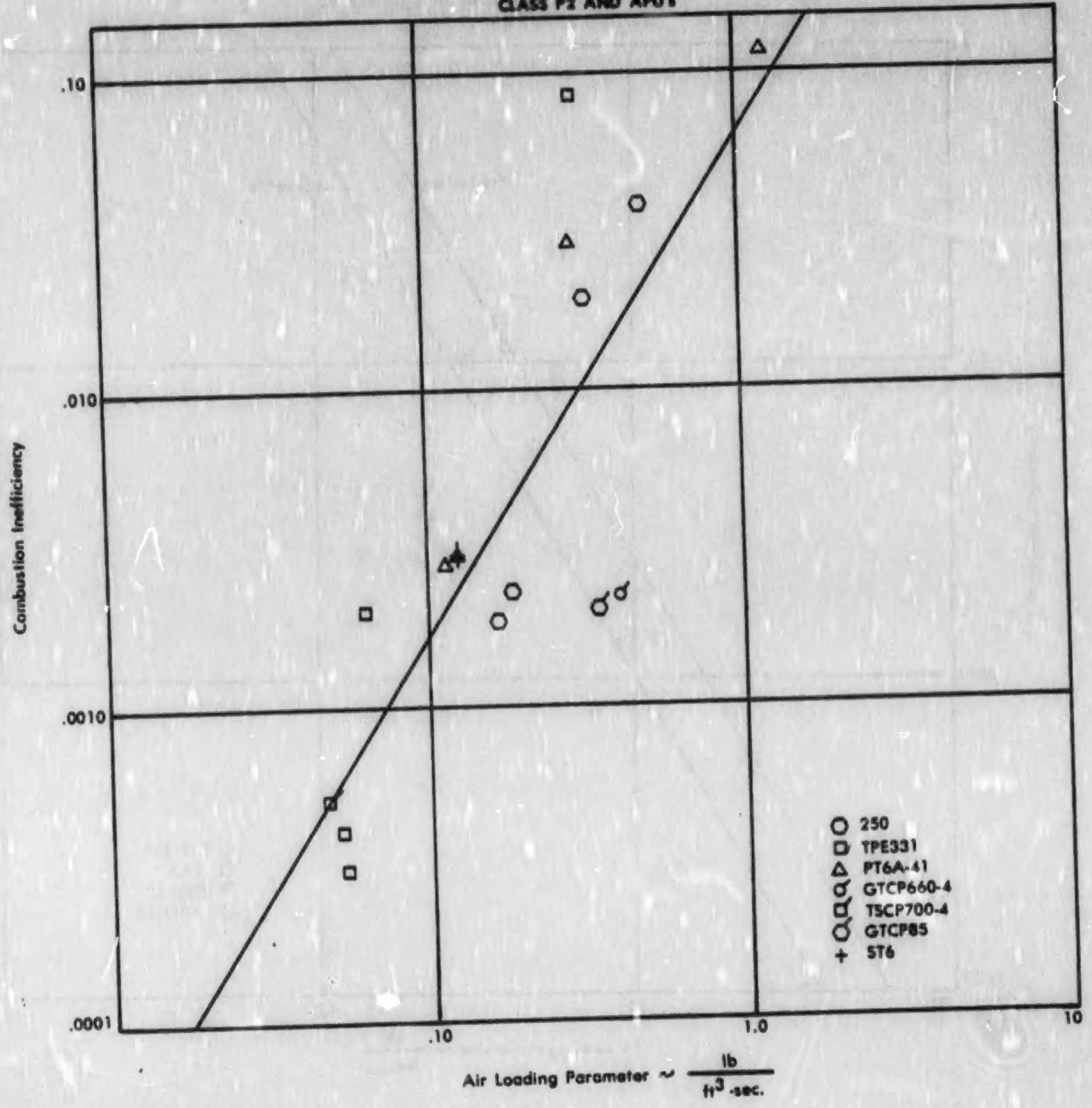


Figure 20

COMBUSTION INEFFICIENCY AS A FUNCTION OF AIR LOADING PARAMETER
ADVANCED COMBUSTOR CONCEPTS
CLASS T2

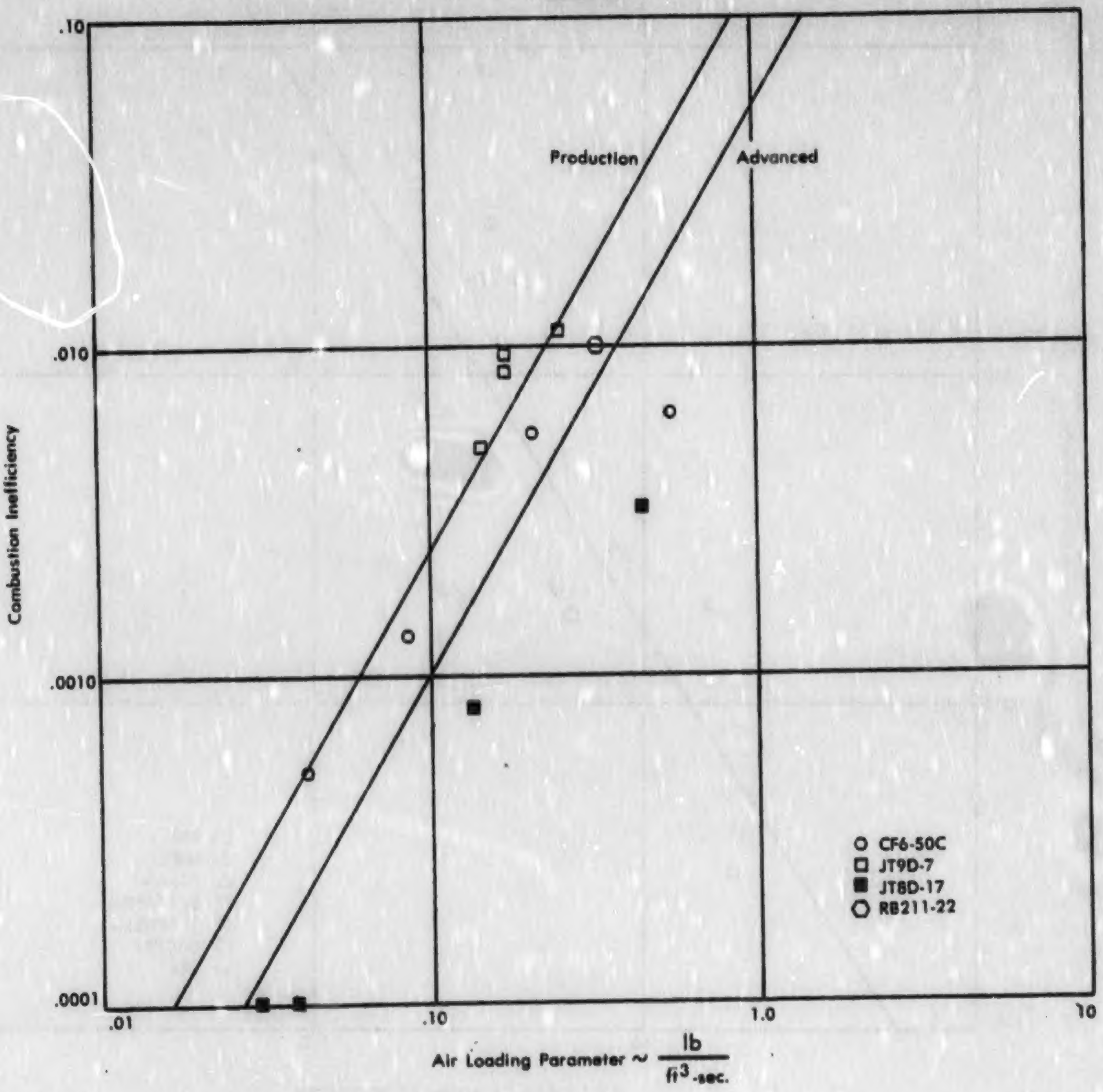


Figure 21

COMBUSTION INEFFICIENCY AS A FUNCTION OF AIR LOADING PARAMETER
ADVANCED COMBUSTOR CONCEPTS
CLASS T1

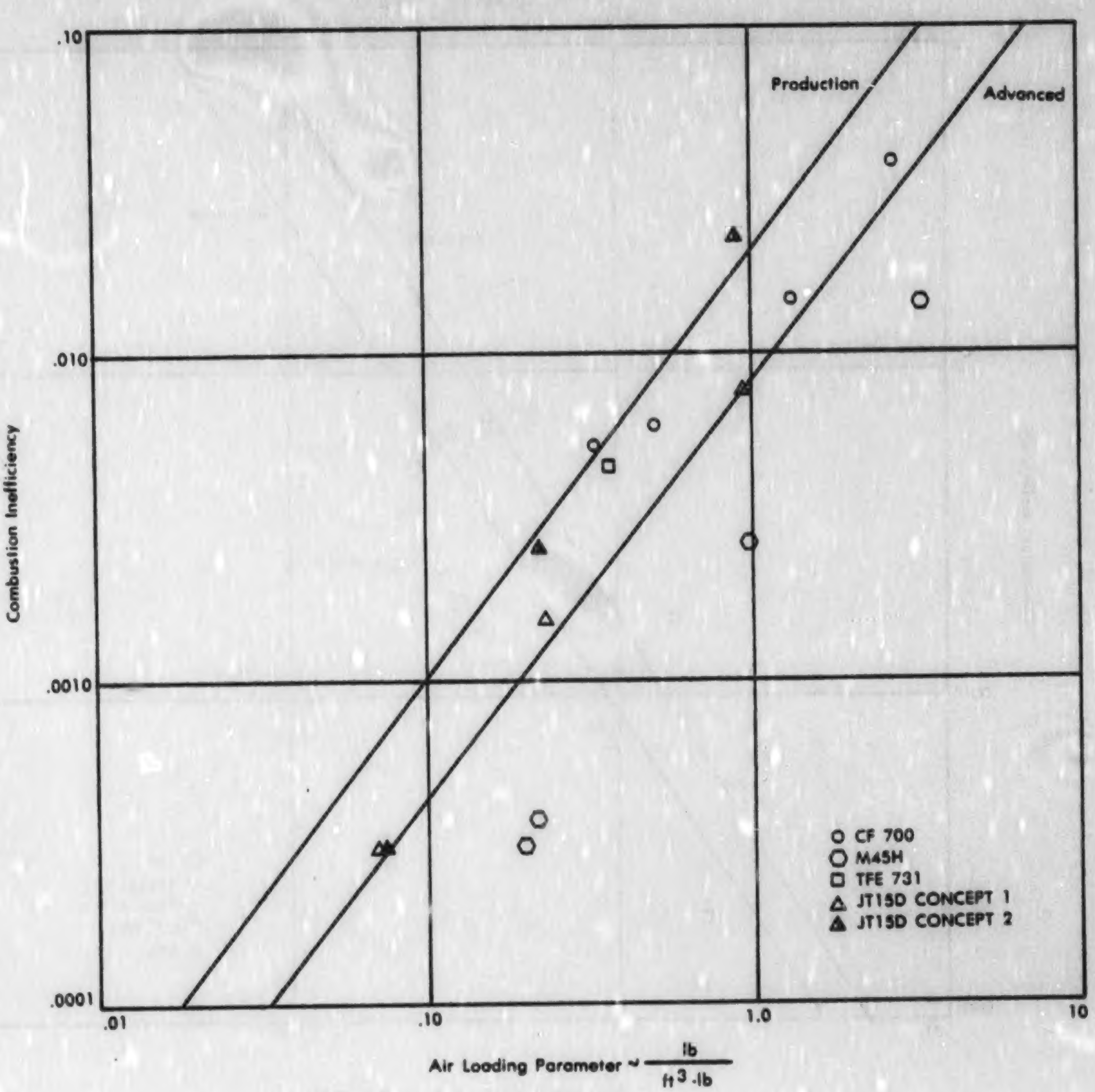


Figure 22

COMBUSTION INEFFICIENCY AS A FUNCTION OF AIR LOADING PARAMETER
ADVANCED COMBUSTOR CONCEPTS
CLASS P2 AND APU's

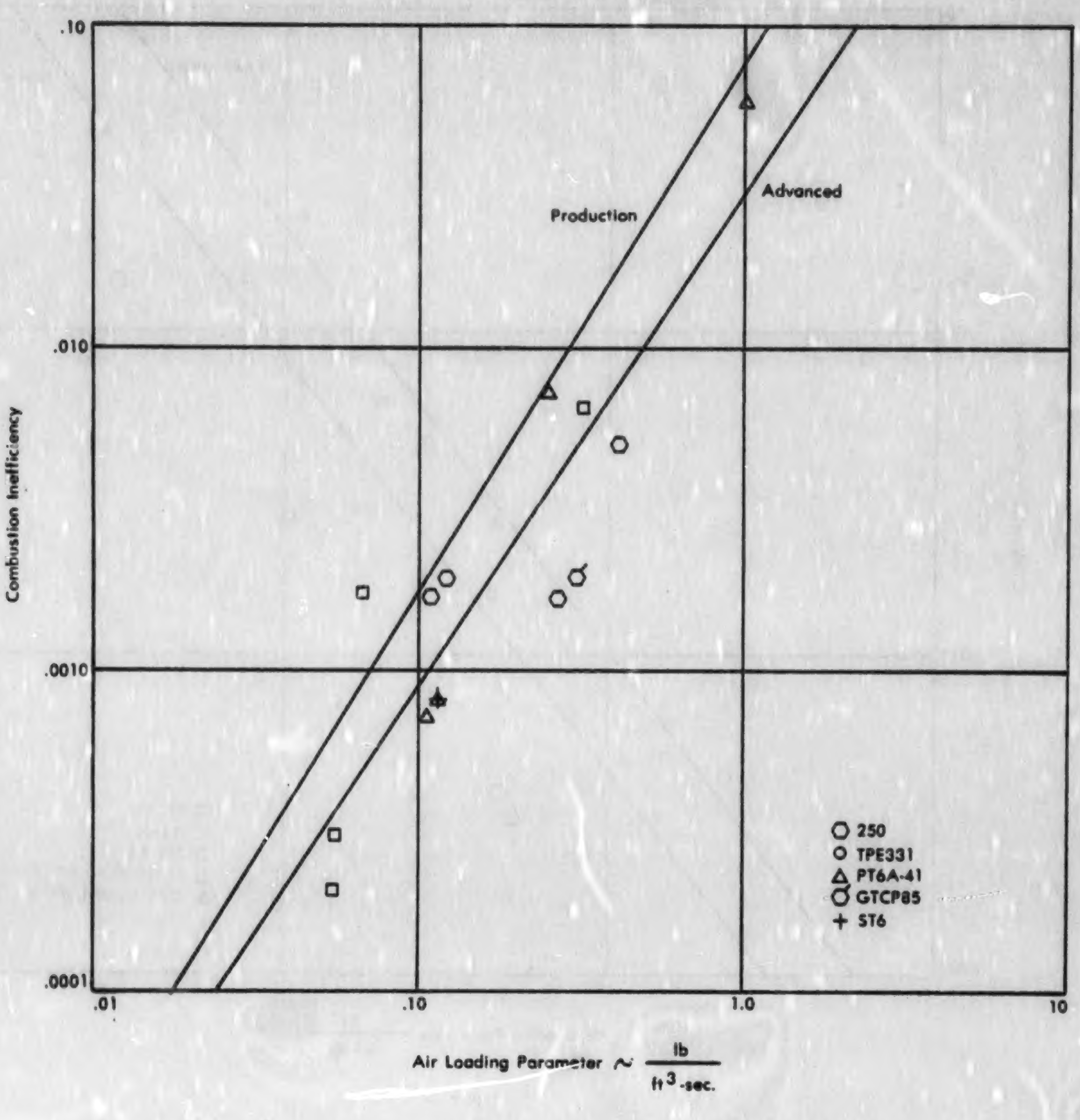


Figure 23

NOX EMISSIONS INDEX AS A FUNCTION OF COMPRESSOR
DISCHARGE TEMPERATURE
PRODUCTION ENGINES
CLASS T2

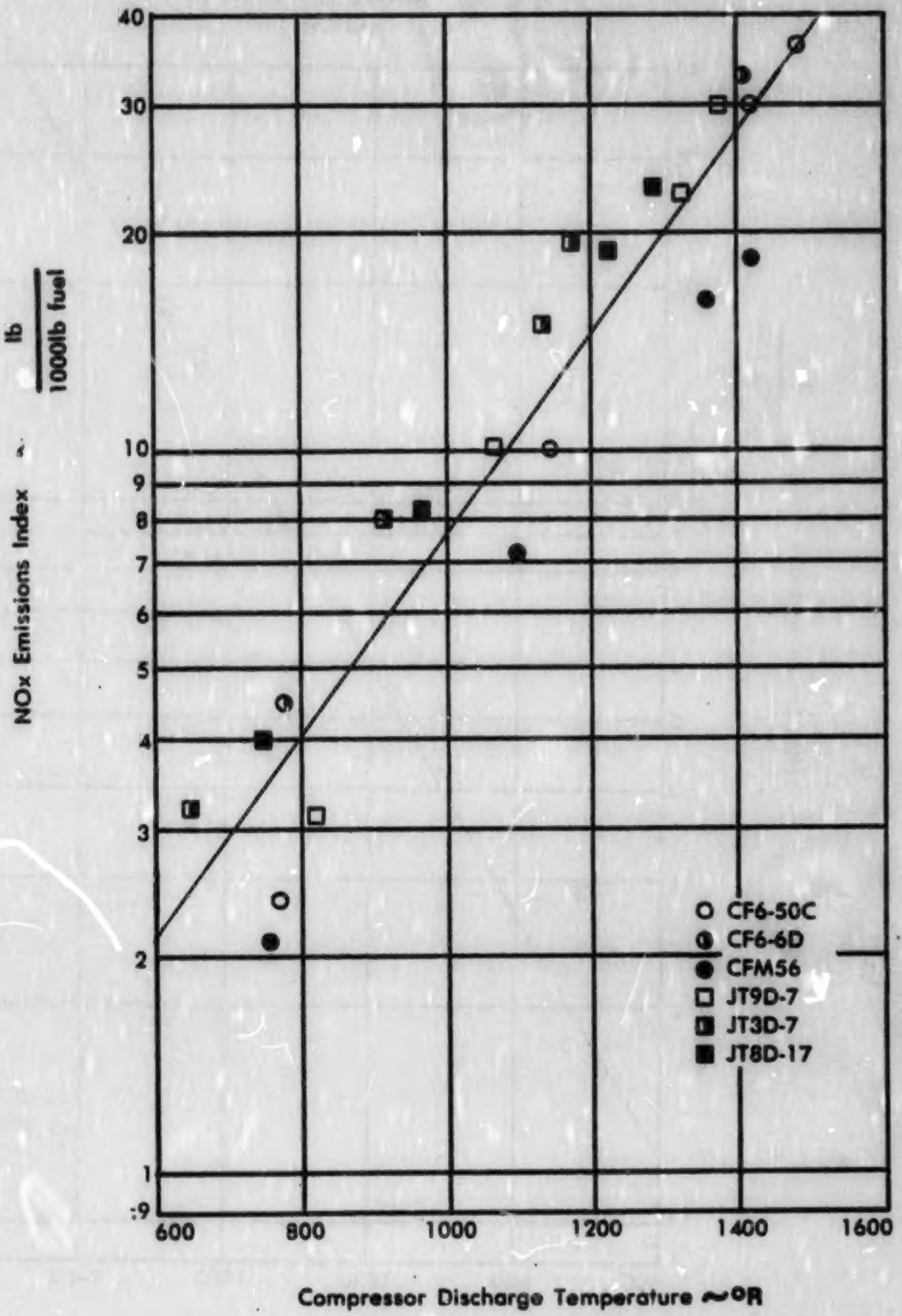


Figure 24

NOX EMISSIONS INDEX AS A FUNCTION OF COMPRESSOR DISCHARGE TEMPERATURE
PRODUCTION ENGINES
CLASS T1

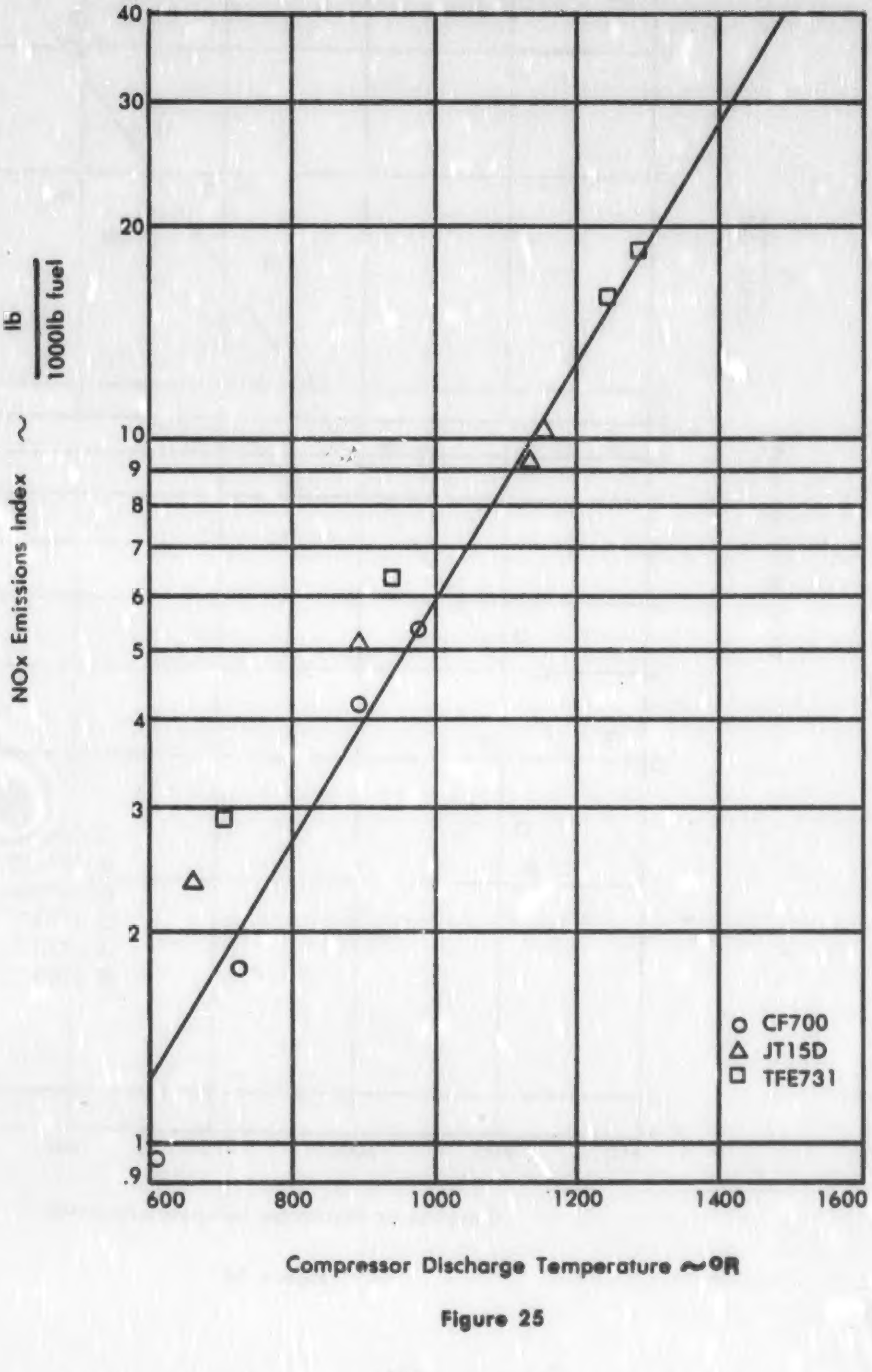


Figure 25

NOX EMISSIONS INDEX AS A FUNCTION OF COMPRESSOR DISCHARGE TEMPERATURE
PRODUCTION ENGINES
CLASS P2 AND APU's

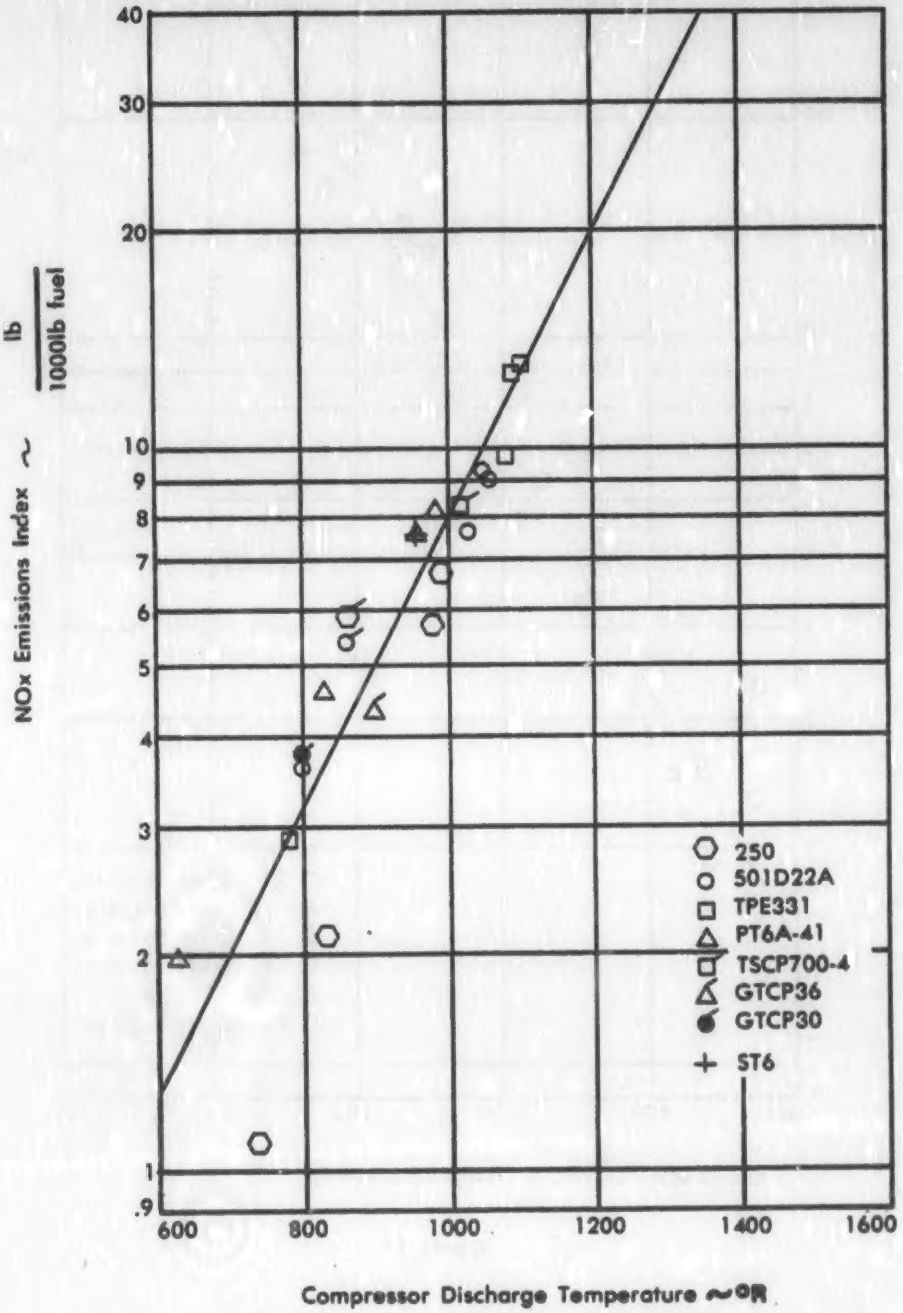


Figure 26

NOx EMISSIONS INDEX AS A FUNCTION OF COMPRESSOR DISCHARGE PRESSURE
PRODUCTION ENGINES

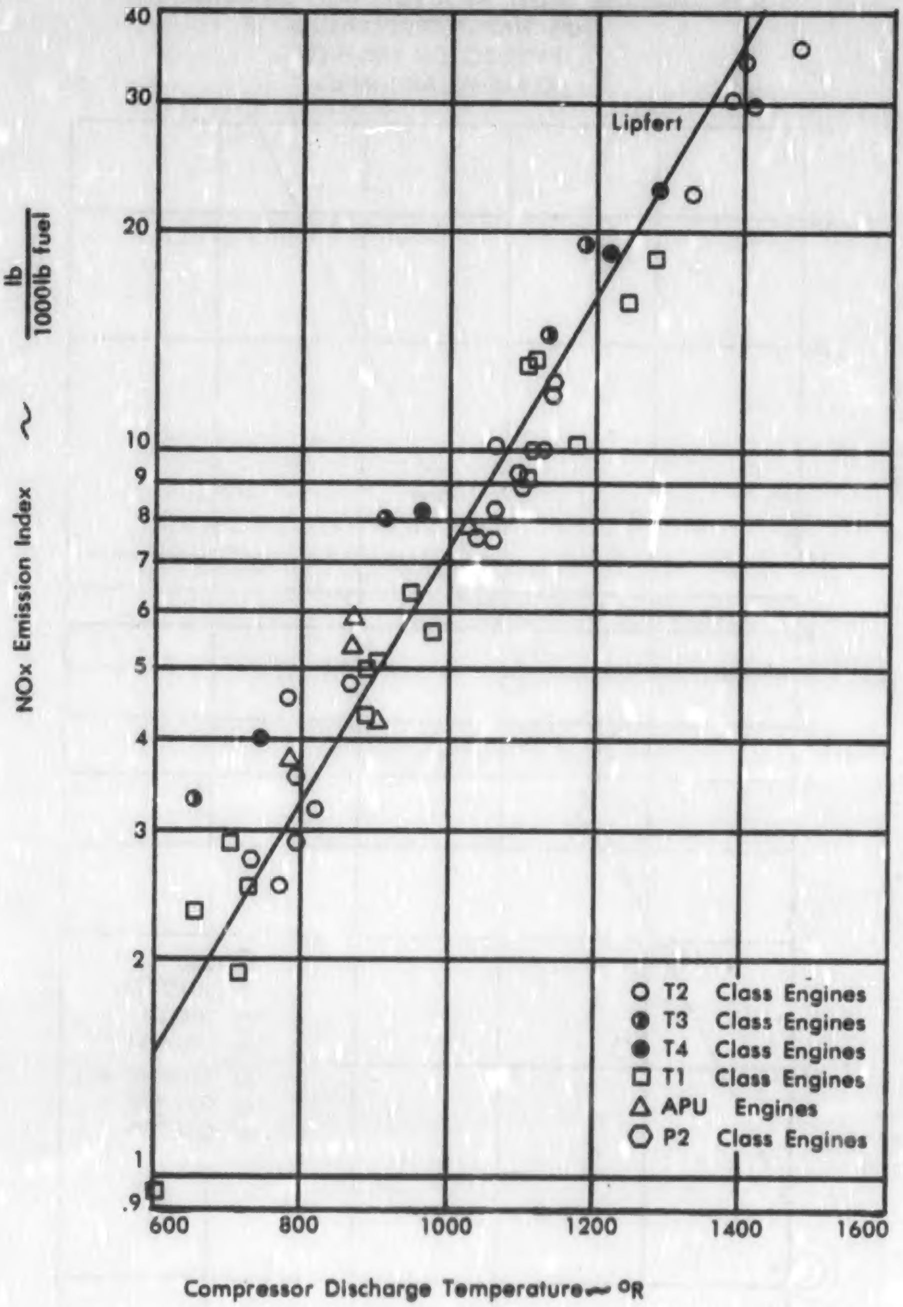


Figure 27

NOX EMISSIONS INDEX AS A FUNCTION OF COMPRESSOR DISCHARGE TEMPERATURE
ADVANCED COMBUSTOR CONCEPTS
CLASS T2

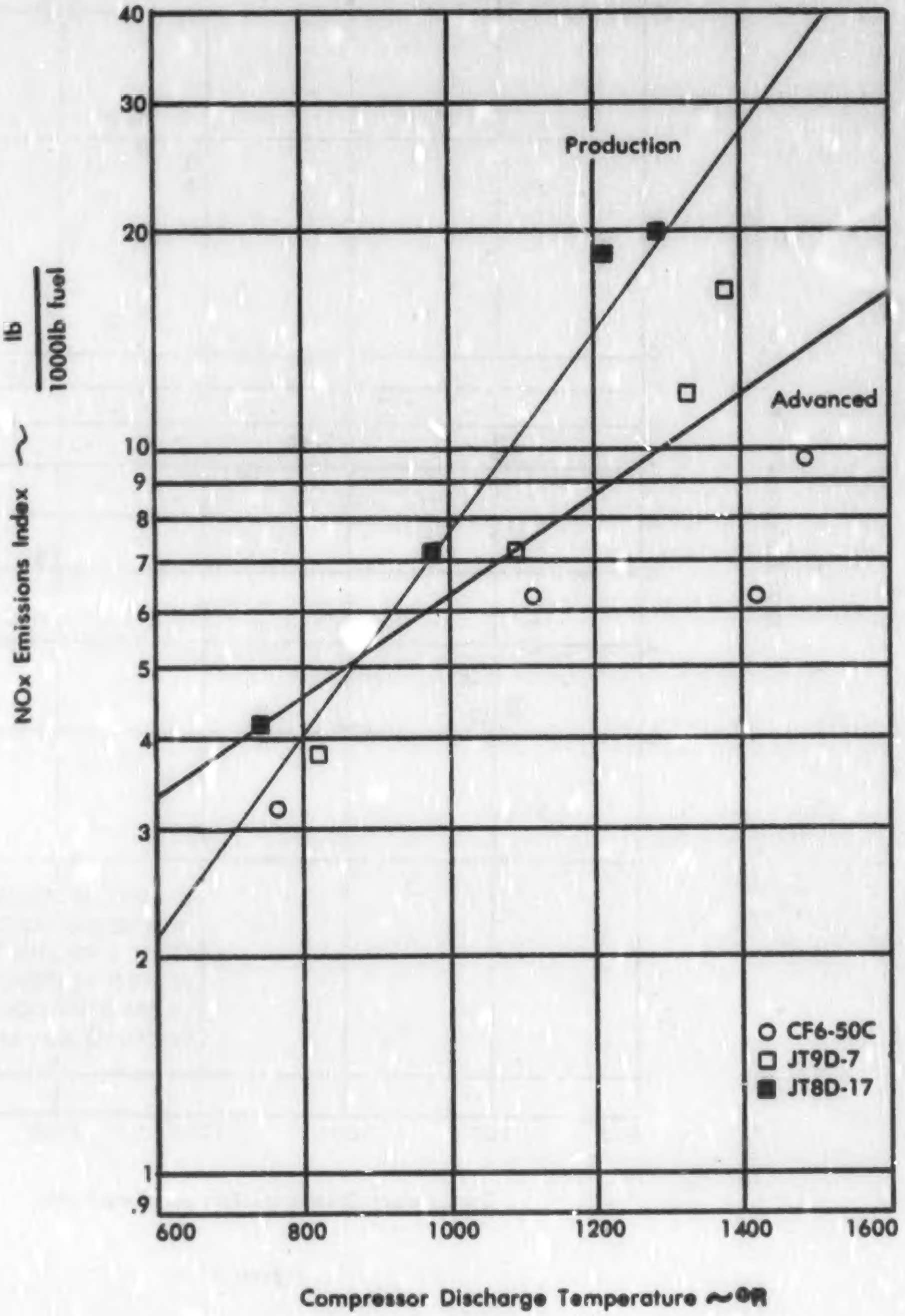


Figure 28

NOX EMISSIONS INDEX AS A FUNCTION OF COMPRESSOR DISCHARGE TEMPERATURE
PRODUCTION ENGINES AND ADVANCED COMBUSTOR CONCEPTS
CLASS T2

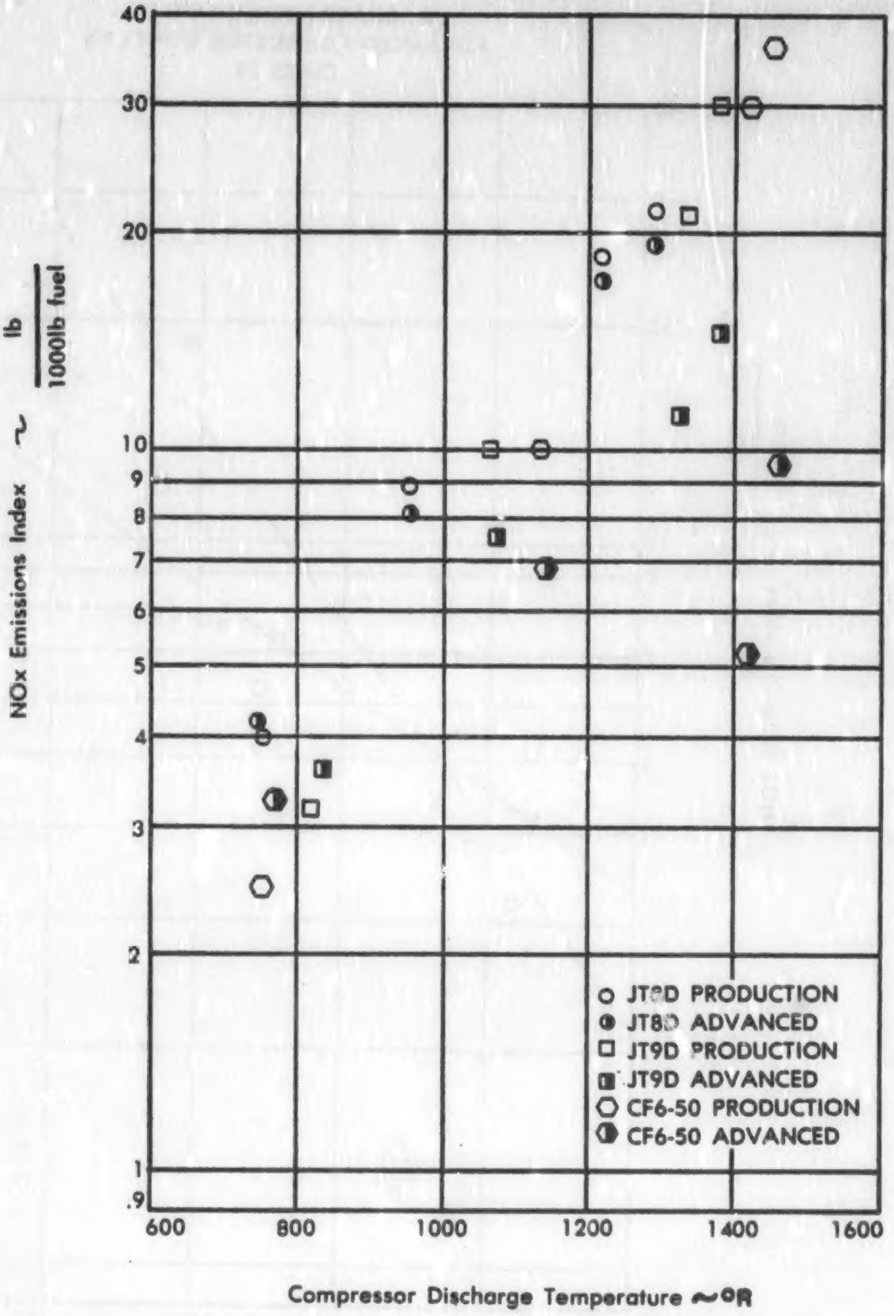


Figure 29

NOX EMISSIONS INDEX AS A FUNCTION OF COMPRESSOR DISCHARGE TEMPERATURE
ADVANCED COMBUSTOR CONCEPTS
CLASS T1

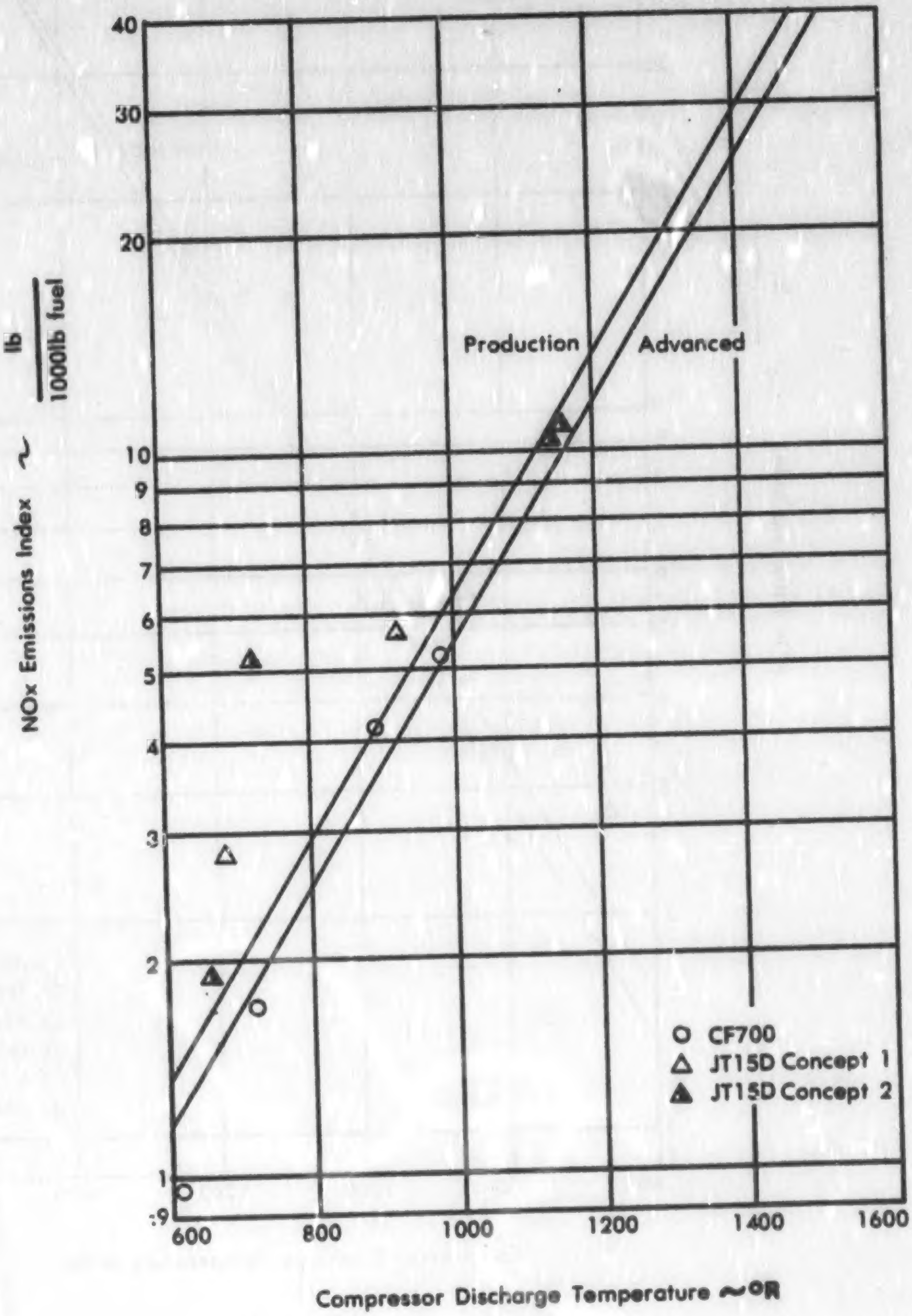


Figure 30

NOX EMISSIONS INDEX AS A FUNCTION OF COMPRESSOR DISCHARGE TEMPERATURE
ADVANCED COMBUTOR CONCEPTS
CLASS P2 AND APU's

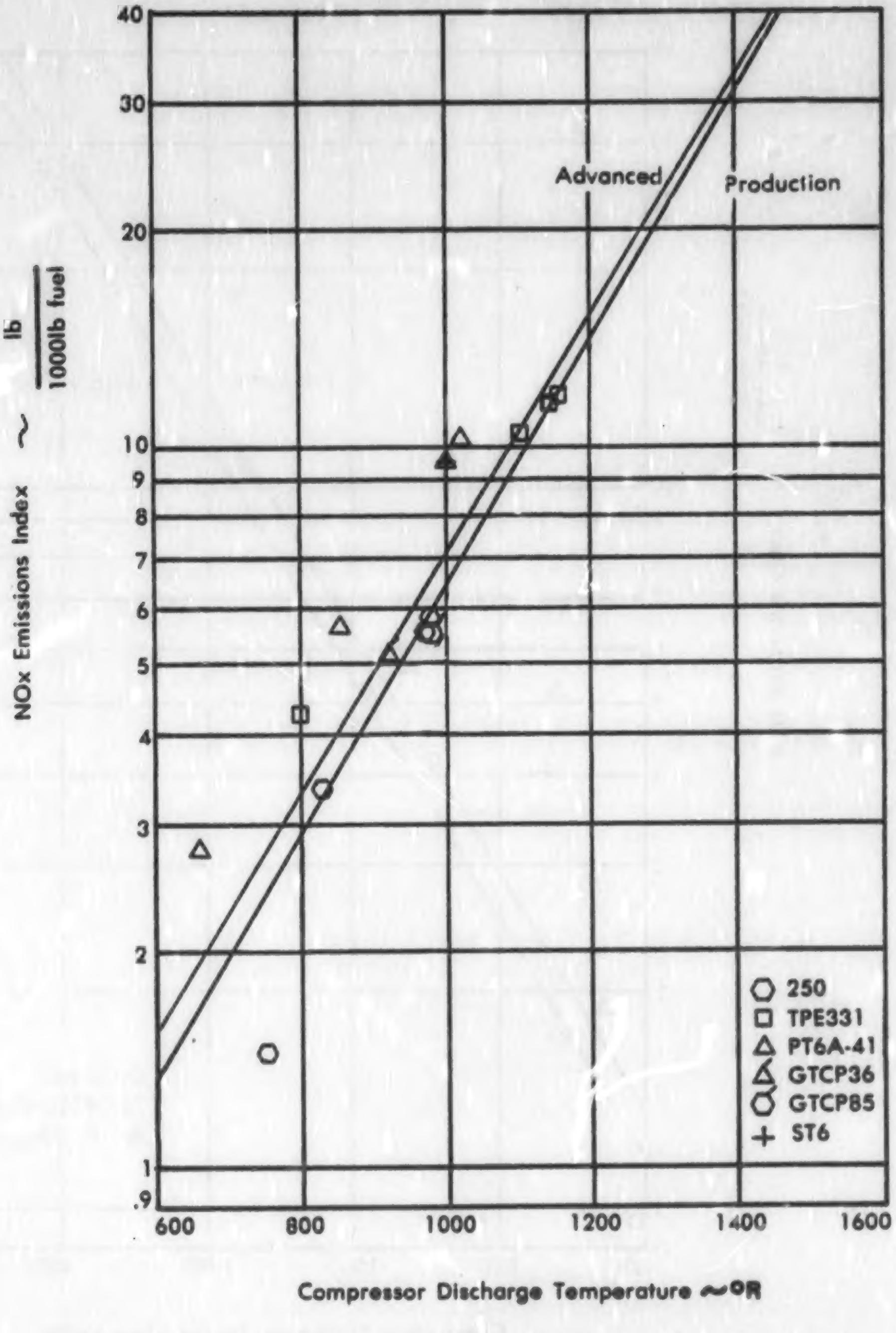


Figure 31

Section 8 - Leadtime Analysis

A peculiar problem exists in the aircraft engine industry, that of the long delay from identification of technology to incorporation in aircraft engines. There is now only a three year period before the regulations become effective and while much work has been accomplished, primarily to identify what is necessary to satisfy the standards, the question is raised again whether the industry will be able to comply with the standards by January 1, 1979.

The time it takes to comply with the standards is readily broken into two divisions; first, the time necessary to identify the method by which the emissions will be reduced satisfactorily and second, the time necessary to incorporate that change into the production hardware. Schematically,

Requirement Specified ←—— A ——→ Technology Identified ←—— B ——→ Requirement Satisified

The first period of time, labeled "A", involves "shotgun" experimentation, parametric experimentation, and possibly analytical studies of sufficient magnitude and duration to identify a control method which, if refined, would perform satisfactorily in the application. The second period of time, labeled "B", involves refinement and optimization of the technology in rig tests, engine tests, qualification, and introduction into production. The discussion that follows will consider each of these times separately.

A. Time necessary to identify the requisite technology:

Programs to identify the necessary technology to comply with the EPA 1979 standards have been carried out on essentially all engines expected to be in production in 1979. In some instances, the bulk of the work is directed towards only one member of a family of engines with the idea that the control technique chosen for that engine will be appropriate, with only minor adaptations, in other closely related engines. Baseline emissions testing of the existing production engines to gauge the magnitude of the problem is done first as a means of sorting out control concepts which would be totally inadequate. Other concepts are then selected for screening in rig tests on the basis of their history of success, if any, convenience to the manufacturer or the user, and the physical constraints imposed either by the engine itself or its operating requirements. Totally new and untried concepts may also be included for general investigative purposes.

"Shotgun" testing of these concepts will identify those which are unacceptable. The difficulty encountered here is that a design for low emissions is often contrary to the design for good operational performance (durability, relight, etc.). These conflicting requirements will render some control methods unacceptable and will lead to difficulties in the perfection of others. Parametric testing is necessary to estimate the extent to which any given approach can be optimized: The originally tested version usually has inadequate emissions performance, but often can be improved in later modifications to satisfy the requirements of the standards (Task 1, period B, discussion below).

For most engines affected by the 1979 standards, acceptable control techniques have been identified, at least for HC and CO. The availability of acceptable NOx control methods is less widespread. Below is a table (8-I) of the engines and their emission control development status expressed as future time required to identify acceptable emissions control techniques. In the cases where an emissions control scheme has not been identified as yet for a particular engine, an estimate in months is presented (Time (1), Time (2)), for the additional time required to complete the screening process for an acceptable solution. As it is usually NOx control that is causing the roadblock, the second scenario (Time (2)) is listed wherein it is assumed that the relevant 1979 NOx standard is raised by 50%. This table must be read with some flexibility, however. Some of the data from the time estimates were made are not as current as other data and more progress has been made in the interim. Consistent, up to date information on the status of development programs is needed prior to the final report. These estimates were made by the EPA and are based upon a review of the best demonstrated technology, the baseline emissions, the amount of screening done so far, and the problems peculiar to a given engine (eg., APUs operate at full power with very low pressure ratios).

Consideration must be given to the few instances, where no satisfactory resolution of the problem can be identified because the necessary technology is more sophisticated than can practicably be incorporated into the engine. The options are then (1) redesign substantial portions of the engine to allow for the use of other technical approaches not feasible in the first screening, (2) cease production of the engine, or (3) make adjustments or exceptions to the regulations. Such a case confronts the CJ610/CF700 engine family.

Table 8-I Lead Time Table

Class	Engine	Time(1)*	Time(2)*	Comment
T1	TF34	-	-	No data Civilian certification uncertain
	CF700	-	-	Will not comply
	CJ610	-	-	Will not comply
	TFE731	12m	0m#	For time (1) Water injection is likely
	ATF3	-	-	No data Civilian certification uncertain
	JT15D	12m	0m	
	JT12A	-	-	Will not comply
	ALF502	18m	12m	NOx uncertain
	M45H	0m	0m	
	RB401	-	-	No data
T2,T3,T4	CF6-6	0m	0m	Time (1) requires water injection, Use CF6-50 technology
	CF6-50	0m	0m	Time (1) requires water injection
	CFM-56	6m	6m	Time (1) requires water injection
	JT3D	-	-	Will not comply
	JT8D	-	12m	Not likely to comply without adjustment to NOx and CO
	JT9D	0m	0m	Time (1) requires water injection
	JT10D	-	-	Certification due after 1979
	RB211	0m	0m	Time (1) requires water injection
	Spey	-	-	No data
P2	TPE331	0m	0m	Smoke?
	PT6A	0m	0m	
	LTP101	6m	6m	Data uncertain
	250	0m	0m	
	501	0m	0m	
	Dart	-	-	No data
APU	GTCP36	12m	12m	Water injection is not acceptable
	GTCP30	6m	0m	"
	GTCP85	12m	6m	"
	TSCP700	12m	0m	"
	GTCP660	12m	12m	"
	ST6	12m	6m	"

(1) Standards as promulgated
(2) NOx standard raised
* Time in months
# "0m" No further time required to identify an acceptable solution

B. Time necessary to incorporate the low emissions technology into the production hardware:

Once the technical approach has been identified, it must be effectively implemented into production. The time necessary to achieve this depends on the accomplishment of the tasks listed in Figures 1 and 2. The EPA estimates of the time required to complete these tasks are derived from the times involved in Phase II and III of the NASA Experimental Clean Combustor Program, communications with the manufacturers, EPA experience with smoke reduction programs, and explanations in EPA Report No. 1168-1, "Assessment of Aircraft Emission Control Technology", September, 1971. The NASA program times are concerned with the demonstration of the technology in rig and engine prototype tests, while the manufacturer and EPA times are concerned with engine certification, checkout, and production preparation times.

Figures 1 and 2 comprise the EPA interpretation of the opinions of the manufacturers on the often conflicting points of view of the leadtime issue. On these figures, time starts with the successful identification of the control technique to be used, that is, the transition from period A to period B. It must be emphasized that a number of manufacturers are well beyond the starting point at this time.

The tasks are described as follows:

1. Combustor development and demonstration in rig test. At the start of this task, a number of low emissions technology concepts have been applied to a combustor rig and their potential evaluated. Generally such testing does not yield configurations that are optimized with respect to emissions and engine performance. In fact, such configurations are often totally unflightworthy as well as perhaps marginal in emissions performance. Once one or two prospective candidates have been selected for further development, this task begins.

The chosen concept or concepts must be refined in the rig sufficiently to meet the pertinent standards when applied to the actual engine. Rig testing also permits extensive optimization of the system for safety and reliability. It further permits simulated altitude performance testing (including relight) which otherwise would be very costly in engine tests in altitude chambers, if possible at all. To proceed directly to engine testing without this task would be a high risk venture: The manufacturer would be committed to a design prior to full investigation of the emissions performance, safety aspects, and operating performance of the combustor. The time allotted for this task is 15 months for large engines and 9 months for small ones. For comparison, Phase II of the NASA Experimental Clean Combustor Program, wherein similar work was done, was a 15 month effort.

2. Engine Demonstration. Engine demonstration is necessary, first, to verify that the combustor, which was optimized in the rig

tests of task 1, operates satifactorily in the full engine, and second, to design the necessary fuel control system to achieve that satisfactory performance. Satisfactory performance here means (1) acceptable steady state performance as evidenced by specific fuel consumption within production specification and acceptable turbine inlet temperature profile and (2) acceptable transient performance as evidenced by a acceleration/deceleration times within FAA requirements with sufficient surge margin. The time allotted for this effort is 12 to 15 months, depending on the engine type and the modifications required. For comparison, Phase III of the NASA Experimental Clean Combustor Program in which such work is being performed is 15 months.

3. Production Design and Procurement. This task involves the design and manufacture (in limited numbers) of all the engine parts modified by the low emissions system and the associated tooling. Such engine parts may include, in addition to the combustor liner itself, the inner and outer casing, diffuser, struts, fuel control, and nozzles.

Manufacturing includes the necessary tooling as well as the limited production to supply engines for static and flight testing, qualification, and service evaluation. Proving of the tooling can be accomplished in parallel with the subsequent steps prior to commitment to production. As reported in EPA Report No. 1168-1, September, 1971 and by General Electric in a separate communication this exercise should take a little over 1 1/2 years, much of which can overlap the engine demonstration period as the final configuration is finally identified, thereby requiring only three to four additional months until engine testing can begin.

4. Engine Testing. This activity involves endurance and cyclic testing necessary first to generate an adequate safety record for later flight testing and engine qualification and second to develop a maintenance and reliability record for service. This is a continuous effort throughout the service life of the engine, but only eight months are necessary before sufficient time is accumulated to begin flight tests if an intensive test schedule is used. In comparison, General Electric suggested that about fourteen months be given to ground testing before flight testing begins. Small engines requiring less extensive modification than the T2 class engines should have less difficulty adhering to this schedule and, indeed, can probably accomplish the necessary preflight testing in six months.

5. Flight Testing. This is done primarily to investigate engine performance at altitude. It is usually done on a corporate owned experimental aircraft or an available military aircraft neither of which are subject to the FAA requirements of certification. Included in the engine performance criteria are thrust, specific fuel consumption, relight, and transient behavior. Environmental factors such as icing, etc. may be investigated as necessary. The T2 class engine manufacturers generally allocate about six months to flight testing prior to start of

qualification while T1 and P2 class engine manufacturers apparently often get by with less, perhaps three months.

6. Qualification. This step involves obtaining the necessary type certificate, supplemental type certificate, or engineering approval for the low emissions engine. The amount of effort involved here is largely dependent upon the type of certification necessary. In any case, FAA certification here involves mostly paperwork as a large part of the necessary testing has already been done. Following the recommendation of several of the manufacturers, six months is delegated to this task.

7. Service Evaluation. Once an engine has the necessary FAA certification or approval, it is, strictly speaking, available for public use. Nonetheless, another stage of testing, that of service evaluation, has developed as a matter of industry policy prior to full production. The procedure in service evaluation is to have a limited number of engines installed on fleet aircraft (one per plane) for a long enough period of time to judge their performance, reliability, and maintainability in actual use. While reliability may be considered a safety issue (the FAA considers service evaluation a vital supplement to its own required testing for certification), it is intended primarily to prove the economics of the engine in service. The length of time of the service evaluation depends upon the rate at which flight time and landing-takeoff cycles are accumulated in service and the extent to which the new system differs from the old (an exotic system will be scrutinized more thoroughly for reliability). A system which has had a history of difficulty in development will command a longer service evaluation.

Several manufacturers have indicated that a one year service evaluation would be adequate for their engines. This is a fairly short time, giving a high time of perhaps 3500 hours and 1400 cycles for commercial engines and somewhat less for general aviation engines. However, this is supported by EPA Report No. 1168-1, referenced earlier. It should be pointed out, on the other hand, that some service evaluations take longer; for instance, the JT8D and JT3D smoke retrofit programs service evaluations took 1 1/2 to 2 years to complete. However, both represented attempts to install advanced technology in quite mature engines (can and can-annular combustors) and both experienced a history of development problems.

EPA Estimate - T1, P2 classes

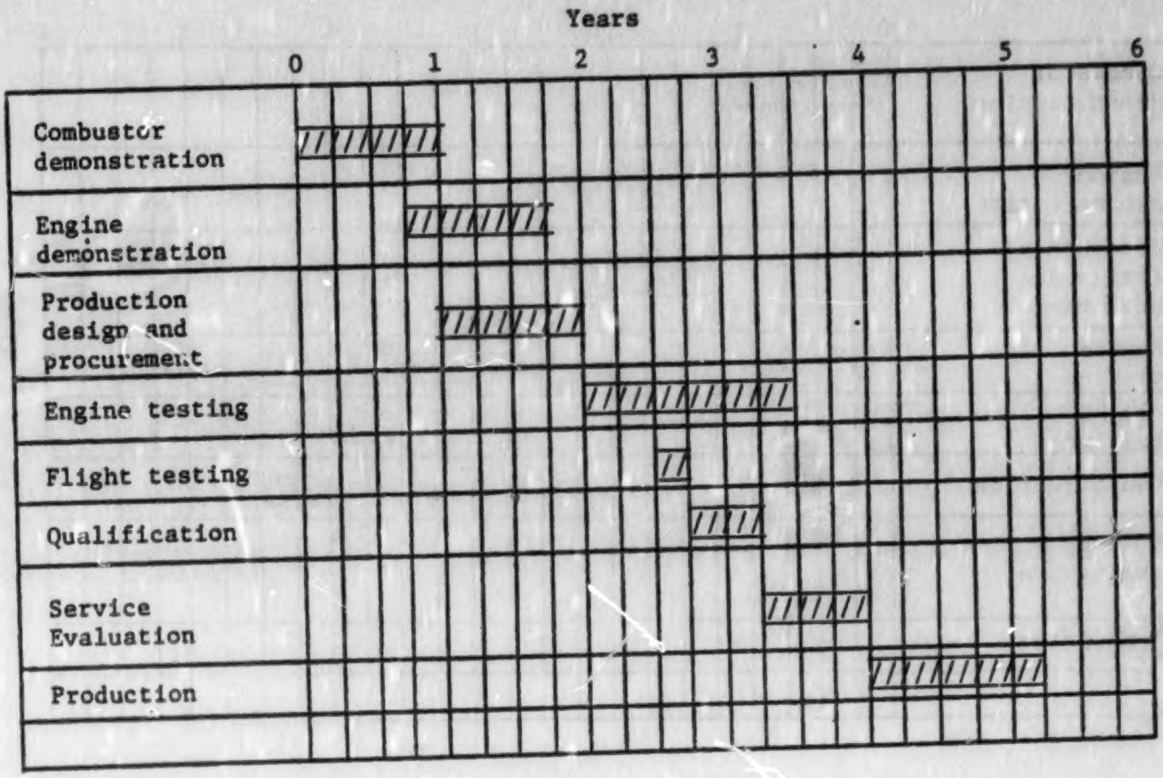


Figure 32

EPA Estimate - T2, T3, T4 Classes

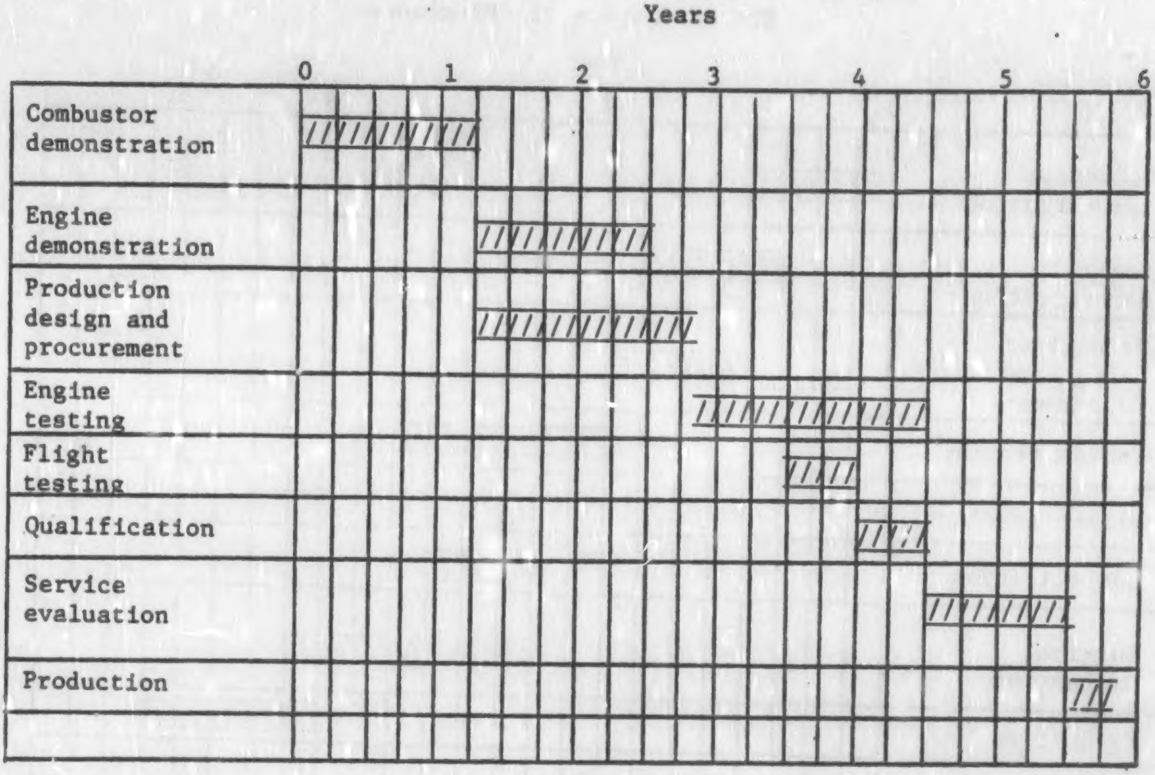


Figure 33

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24. Proposal: Effects of Ambient Conditions on Aircraft Engine Emissions by Combustor Rig Testing, May 19, 1975, AVCO Lycoming.

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Appendix A

Data Bank

ENGINE: ALL. 250B15G
V comb: 0.127 ft^3
S comb: 1.24 ft^2
PRODUCTION

T rated: 330 eshp
π_c: 6.2

IDLE POWER: 10 % rated

MODE	P_3 (atm)	T_3 (^oR)	$\dot{M}_a$ (#/S)	Ω	f/a						$1-\eta_c$	EI HC	 CO	 NO_x	
IDLE	3.03	730	1.87	.491	.0109						.0403	20.18	97.35	1.45	
APPROACH	3.78	830	2.32	.359	.0124						.0158	5.18	48.6	2.18	
CLIMBOUT	5.99	965	3.14	.166	.0185						.0024	0.38	9.0	5.95	
TAKEOFF	6.28	985	3.22	.150	.0198						.0020	0.25	7.83	6.59	
ADVANCED: Prechamber, V=0.18 ft^3, S=1.64 ft^2															
IDLE	3.03	760	1.855	.346	.0109						.0050	2.00	14.01	1.58	
APPROACH	3.78	830	2.32	.256	.0124						.0018	0.23	7.0	3.40	
CLIMBOUT	5.99	965	3.14	.118	.0185						.0018	0.060	7.4	5.52	
TAKEOFF	6.28	985	3.24	.107	.0196						.0014	.0436	5.76	5.81	
ADVANCED: Extended Primary, V=0.21 ft^3, S= 2.53 ft^2															
IDLE															
APPROACH															
CLIMBOUT															
TAKEOFF															

ENGINE: A11 501D22A

V comb:	**T rated:** 4368 eshp	**IDLE POWER:**	5	**% rated**
S comb:	π_c: 9.7			

PRODUCTION

MODE	P_3 (atm)	T_3 (^oR)	$\dot{M}_a$ (#/S)	Ω	f/a						$1-\eta_c$	EI HC	EI CO	EI NO_x
IDLE	3.64	795	15.0		.0113	825					.026	17.6	43.6	3.53
APPROACH	8.30	1059	33.0		.0096						.0029	1.96	5.10	7.49
CLIMBOUT	9.45	1091	33.0		.0185						.0013	0.89	2.06	9.22
TAKEOFF	9.70	1099	33.0		.0200	1281					.0007	0.28	2.04	8.88
ADVANCED: Reverse Flow Mod 1														
IDLE											.0014	0.61	3.88	4.05
APPROACH											.0009	0.55	1.83	6.48
CLIMBOUT											.0007	0.52	1.01	10.57
TAKEOFF											.0009	0.77	0.95	10.64
ADVANCED: Prechamber Baseline														
IDLE											.0007	0.40	1.53	1.86
APPROACH											.0065	5.00	9.13	5.80
CLIMBOUT											.0010	0.47	2.64	11.16
TAKEOFF											.0005	0.08	1.64	11.23

ENGINE: TPE331
V comb: .265 ft^3
S comb: 4.01 ft^4
PRODUCTION

T rated: 840 SHP
π_c: 10.57

IDLE POWER: 5 % rated

												EI		
MODE	P_3 (atm)	T_3 (°R)	$\dot{M}_a$ (#/S)	Ω	f/a						$1-\eta_c$	HC	CO	NO_x
IDLE	3.07	793	2.61	.301	.0119						.084	79.11	61.53	2.867
APPROACH	9.11	1122	7.31	.065	.0095						.002	.624	6.94	9.901
CLIMBOUT	9.99	1142	7.15	.052	.0159						.0004	.139	.973	11.851
TAKEOFF	10.09	1145	7.62	.054	.0167						.0003	.102	.766	12.358
ADVANCED:														
IDLE	3.19	797	3.01	.322	.0097						.0065	2.704	17.612	4.209
APPROACH	8.86	1123	7.38	.069	.0093						.0017	.300	6.279	10.612
CLIMBOUT	9.57	1140	7.20	.056	.0152						.0003	.064	1.141	12.125
TAKEOFF	9.72	1142	7.26	.055	.0161						.0002	0.20	.373	12.571
ADVANCED:														
IDLE														
APPROACH														
CLIMBOUT														
TAKEOFF														

ENGINE: LTP101
V comb: T rated: 610 eshp IDLE POWER: 4.6 % rated
S comb: π_c: 8.3
PRODUCTION

MODE	P_3 (atm)	T_3 (^oR)	$\dot{M}_a$ (#/S)	Ω	f/a						$1-\eta_c$	EI			
												HC	CO	NO_x	
IDLE	3.33	830	2.32		.0115						.030	19.2	45		
2X IDLE	4.01	910	2.78		.0114										
APPROACH	5.03	935	3.26		.0133										
CLIMBOUT	8.0	1059	4.64		.0185										
TAKEOFF	8.3	1078	4.78		.0195										
ADVANCED:															
IDLE															
APPROACH															
CLIMBOUT															
TAKEOFF															
ADVANCED:															
IDLE															
APPROACH															
CLIMBOUT															
TAKEOFF															

ENGINE: T5321A
V comb:
S comb:
PRODUCTION

T rated: 1,800 eshp
π_c: 8.0

IDLE POWER: 7 % rated

													EI		
MODE	P_3 (atm)	T_3 (^oR)	$\dot{M}_a$ (#/S)	Ω	f/a						$1-\eta_c$	HC	CO	NO_x	
IDLE	2.6	758	6.0		.0130										
APPROACH	4.81	895	9.2		.0148										
CLIMBOUT	7.75	1072	13.9		.0207										
TAKEOFF	8	1100	14.1		.0217										
ADVANCED:															
IDLE															
APPROACH															
CLIMBOUT															
TAKEOFF															
ADVANCED:															
IDLE															
APPROACH															
CLIMBOUT															
TAKEOFF															

ENGINE: T53-L-13A

V comb: T rated: 1400 shp **IDLE POWER:** 7 **% rated**

S comb: π_c: 7

PRODUCTION

MODE	P_3 (atm)	T_3 (^oR)	$\dot{M}_a$ (#/S)	Ω	f/a						$1-\eta_c$	EI HC	 CO	 NO_x	
IDLE	2.38	733	4.7		.0130							9.52	33.94	2.71	
APPROACH	4.39	868	7.2		.0148							0.39	5.97	4.78	
CLIMBOUT	7.07	1040	10.8		.0207							-	0.97	7.58	
TAKEOFF	7.3	1066	11.0		.0217							-	0.84	8.23	
ADVANCED:															
IDLE															
APPROACH															
CLIMBOUT															
TAKEOFF															
ADVANCED:															
IDLE															
APPROACH															
CLIMBOUT															
TAKEOFF															

ENGINE: PT6A-41
V comb: .26 ft^3
S comb: 3.66 ft^2
PRODUCTION

T rated: eshp
π_c: 8.26

IDLE POWER: 3 % rated

												EI			
MODE	P_3 (atm)	T_3 (^oR)	$\dot{M}_a$ (#/S)	Ω	f/a	ΔT_c	NSP				$1-\eta_c$	HC	CO	NO_x	
IDLE	2.00	628	3.53	1.219	.0116						.12	101.6	115.3	1.98	
APPROACH	4.89	837	6.39	.300	.0118						.029	22.7	34.8	4.65	
CLIMBOUT	7.76	982	8.22	.128	.0161						.003	2.02	6.48	7.56	
TAKEOFF	8.12	1001	8.49	.118	.0168						.0028	1.75	5.06	7.98	
ADVANCED: MOD. A															
IDLE	2.16	660	3.72	1.054	.0095						.0563	35.5	66.9	2.79	
APPROACH	5.01	867	5.97	.254	.0122						.0072	3.39	14.36	6.08	
CLIMBOUT	8.03	1005	8.18	.115	.0166						.0008	.32	1.55	9.45	
TAKEOFF	8.42	1017	8.46	.107	.0169						.0007	0.3	1.2	10.2	
ADVANCED:															
IDLE															
APPROACH															
CLIMBOUT															
TAKEOFF															

ENGINE: GTCP30
V comb:
S comb:
PRODUCTION

T rated: 78HP
π_c: 3.76

POWER	P_3 (atm)	T_3 (^oR)	$\dot{M}_a$ (#/S)	Ω	f/a						$1-\eta_c$	EI HC	 CO	 NO_x	
	2.43	687	.947		.0198						.0014	.110	5.576	3.506	
	2.48	790	.963		.0199						.0014	.139	5.549	3.620	
78 HP	2.52	794	.954		.0201						.0013	.139	5.259	3.706	
ADVANCED:															
ADVANCED:															

ENGINE: GTCP36-50

V comb:

S comb:

PRODUCTION

T rated: 103 HP

π_c: 3.25

												EI		
POWER	P_3 (atm)	T_3 (^oR)	M_a (#/S)	Ω	f/a						$1-\eta_c$	HC	CO	NO_x
79 HP	3.32	882	1.91		.017						.0057	.346	23.066	4.100
94 HP	3.47	893	1.96		.018						.0043	.141	17.793	4.332
103 HP	3.57	906	1.88		.020						.0028	.044	11.645	4.253
ADVANCED:	Airblast													
	.997	923	2.35		.0113						.0101	1.042	38.88	5.175
	.997	926	1.77		.0207						.0018	.041	7.395	5.111
ADVANCED:														

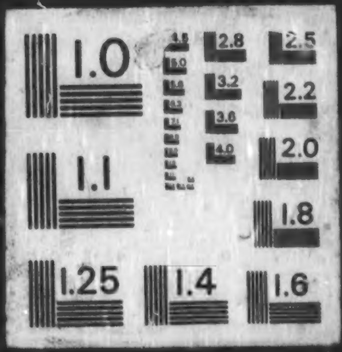
ENGINE: GTCP85-98
V comb: .229 ft^3/can **T rated:** 293 HP
S comb: 1.99 ft^2/can π_c: 3.36
PRODUCTION

POWER	P_3 (atm)	T_3 (^oR)	$\dot{M}_a$ (#/S)	Ω	f/a						1-η_c	EI HC	 CO	 NO_x	
243 HP	3.30	863	3.97	.409	.019						.0023	.182	9.164	5.411	
277 HP	3.60	870	4.26	.370	.019						.0022	.163	8.87	5.593	
293 HP	3.74	876	4.36	.350	.019						.0020	.145	7.972	5.856	
ADVANCED:	Wide Spray	angle cone													
	3.51	1000	4.21	.301	.0147						.0025	.173	9.809	5.73	
237 HP	3.29	990	3.79	.310	.0178						.0019	.077	7.876	5.780	
ADVANCED:															

2 OF 2

PB

270262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1.6

ENGINE: TSCP700-4

V comb: .560 ft^3 T rated: 772 HP

S comb: 4.62 ft^2 π_c: 10.37

PRODUCTION

	P_3	T_3	$\dot{M}_a$									EI			
POWER	(atm)	(^oR)	(#/S)	Ω	f/a						$1-\eta_c$	HC	CO	NO_x	
639 HP	6.96	992	6.75	.058	.020						.0005	.183	1.550	7.108	
704 HP	7.16	1001	7.00	.056	.020						.0006	.244	1.446	7.377	
772 HP	7.77	1028	7.29	.048	.020						.0005	.189	1.328	7.806	
ADVANCED:															
ADVANCED:															

ENGINE: GTCP660-4
V comb: .866 ft^3 **T rated:** 1141 HP
S comb: 8.23 ft^2 π_c: 3.5
PRODUCTION

													EI		
POWER	P_3 (atm)	T_3 (^oR)	$\dot{M}_a$ (#/S)	Ω	f/a						$1-\eta_c$	HC	CO	NO_x	
958 HP	3.05	854	13.49	.430	.019						.0025	.224	9.608	4.924	
1045 HP	3.24	863	15.19	.428	.018						.0025	.400	8.972	5.119	
1141 HP	3.40	870	15.80	.403	.018						.0022	.305	8.349	5.320	
ADVANCED:															
ADVANCED:															

ENGINE: CF700-2D
V comb: .607 ft^3 T rated: 4500 lbs IDLE POWER: 6.24 % rated
S comb: 5.04 ft^2 π_c: 6.60
PRODUCTION

	P_3	T_3	$\dot{M}_a$									EI			
MODE	(atm)	(°R)	(#/S)	Ω	f/a						$1-\eta_c$	HC	CO	NO_x	
IDLE	1.50	605	10.6	2.745	.012						.052	18.0	155.0	.90	
APPROACH	2.72	716	18.6	1.344	.014						.016	1.4	62.0	1.8	
CLIMBOUT	5.78	890	38.4	.518	.017						.0059	0.1	25.0	4.3	
TAKEOFF	6.94	980	41	.337	.018						.0052	0.1	22.0	5.6	
ADVANCED:	Reduced core angle														
IDLE	1.50	605	10.6	2.745	.012						.038	2.45	155.0	.90	
APPROACH	2.72	716	18.6	1.344	.014						.0145	.57	60.28	1.8	
CLIMBOUT	5.78	890	38.4	.518	.017						.0059	0.1	25.0	4.3	
TAKEOFF	6.99	980	41	.337	.018						.0052	0.1	22.0	5.6	
ADVANCED:															
IDLE															
APPROACH															
CLIMBOUT															
TAKEOFF															

ENGINE: JT15D
V comb: .55 ft^3 T rated: 2500 lbs **IDLE POWER:** 6 % rated
S comb: 6.16 ft^2 π_c: 10.2
PRODUCTION

MODE	P_3 (atm)	T_3 (^oR)	$\dot{M}_a$ (#/S)	Ω	f/a						$1-\eta_c$	EI HC	 CO	 NO_x
IDLE	1.82	659.11	5.49	1.0412	.0099						.055	36.97	90.94	2.32
APPROACH	4.51	905.9	11.10	.2543	.0125						.0066	2.24	19.5	5.10
CLIMBOUT	9.31	1118.1	20.58	.0849	.0174						.0003	0	1.19	9.10
TAKEOFF	10.12	1147.3	22.23	.0740	.0182						.0002	0	1.01	10.10
ADVANCED:	Mod. Flame Tube													
IDLE	1.78	663.4	5.01	.9541	.0104						.0076	.84	29.43	2.83
APPROACH	4.52	992.2	10.74	.2365	.0132						.0015	.03	6.41	5.75
CLIMBOUT	9.50	1140	19.50	.0745	.0179						.0003	0	.8	10.2
TAKEOFF	10.00	1147	22.00	.0740	.0183						.0003	0	.6	10.3
ADVANCED:	Mod. Flame Tube		Mod. Nozzle											
IDLE	1.78	661.6	4.87	.9304	.0099						.0229	9.56	60.70	1.95
APPROACH	4.59	926.4	10.67	.2269	.0125						.0025	.2	9.78	5.51
CLIMBOUT	9.52	1143.3	19.49	.0745	.0179						.0003	0	1.12	10.05
TAKEOFF	10.00	1147	22.00	.0740	.0183						.0003	0	.6	10

ENGINE: TFE 731

V comb: .706 ft^3 T rated: 3230 lbs IDLE POWER: 6.61 % rated

S comb: 7.00 ft^2 π_c: 12.68

PRODUCTION

												EI			
MODE	P_3 (atm)	T_3 (^oR)	$\dot{M}_a$ (#/S)	Ω	f/a						$1-\eta_c$	HC	CO	NO_x	
IDLE	1.84	702.5	5.33	.686	.0097						.035	23.03	62.67	2.88	
APPROACH	4.60	950.3	12.15	.190	.0118						.006	2.56	16.27	6.37	
CLIMBOUT	11.08	1243.9	25.92	.048	.0147						.0003	.012	1.26	15.80	
TAKEOFF	12.15	1283.7	27.73	.041	.0155						.0003	.077	1.02	18.13	
ADVANCED:	Air assist at taxi idle														
IDLE	1.84	950.3	4.57	.372	.0110						,0047	.73	17.46	3.86	
APPROACH															
CLIMBOUT															
TAKEOFF															
ADVANCED:															
IDLE															
APPROACH															
CLIMBOUT															
TAKEOFF															

ENGINE: ALF 502D
V comb:
S comb:
PRODUCTION (F102)

T rated: 6500 lbs
π_c: 6.1

IDLF POWER: 6.1% rated

												EI			
MODE	P_3 (atm)	T_3 (^oR)	$\dot{M}_a$ (#/S)	Ω	f/a						$1-\eta_c$	HC	CO	NO_x	
IDLE		730									.045	17.5	118	2.5	
APPROACH		890	16.5		.0145									5.0	
CLIMBOUT		1110	21.8		.0234									13.0	
TAKEOFF	6.1	1120	22.5		.0246	.021					.001			13.2	
ADVANCED: Airblast (ALF502)															
IDLE		730									.020	6.2	57	4.0	
APPROACH		890												6.8	
CLIMBOUT		1110												13.0	
TAKEOFF		1120												13.2	
ADVANCED:															
IDLE															
APPROACH															
CLIMBOUT															
TAKEOFF															

ENGINE: M45H
V comb:
S comb:
PRODUCTION

T rated: 7500 lbs
π_c: 16

IDLE POWER: 5 % rated

												EI			
MODE	P_3 (atm)	T_3 (°R)	$\dot{M}_a$ (#/S)	Ω	f/a						$1-\eta_c$	HC	CO	NO_x	
IDLE				3.4							.090	81.6	80		
APPROACH				1.0							.019	11.0	40.5		
CLIMBOUT				0.22							.0029	1.0	8.5		
TAKEOFF				0.20							.0026	0.9	8.0		
ADVANCED:															
IDLE				3.4							.014	7.7	31.0		
APPROACH				1.0							.0026	0.9	8.0		
CLIMBOUT				0.22							.00037	0.1	1.4		
TAKEOFF				0.20							.0003[illegible]	0.1	1.3		
ADVANCED:															
IDLE															
APPROACH															
CLIMBOUT															
TAKEOFF															

ENGINE: RB401
V comb:
S comb:
PRODUCTION

T rated:
π_c:

IDLE POWER:

% rated

	P_3	T_3	$\dot{M}_a$									EI			
MODE	(atm)	(^oR)	(#/S)	Ω	f/a						$1-\eta_c$	HC	CO	NO_x	
IDLE															
APPROACH															
CLIMBOUT															
TAKEOFF															
ADVANCED:															
IDLE															
APPROACH															
CLIMBOUT															
TAKEOFF															
ADVANCED:															
IDLE															
APPROACH															
CLIMBOUT															
TAKEOFF															

ENGINE: CF6-50C
V comb: 1.94 ft^3 **T rated:** 51000 lbs **IDLE POWER:** 3.4 % rated
S comb: 16.79 ft^2 π_c: 29.8
PRODUCTION

MODE	P_3 (atm)	T_3 (^oR)	$\dot{M}_a$ (#/S)	Ω	f/a						$1-\eta_c$	EI HC	 CO	 NO_x	
IDLE	2.91	773	31.99	.576	.011						.043	30.0	73.0	2.50	
APPROACH	11.70	1134	104.9	.079	.014						.001	.010	4.30	10.00	
CLIMBOUT	25.85	1415	203.3	.0219	.0214						.00008	.010	.30	29.50	
TAKEOFF	29.80	1477	227.3	.0169	.0231						.00006	.010	.20	35.50	
ADVANCED:	DA Configuartion														
IDLE	2.93	778	30.87	.544	.0113						.006	2.0	19.0	3.4	
APPROACH	3.45	1134	30.65	.208	.0140						.006	.1	23.4	6.3	
CLIMBOUT	4.74	1415	37.70	.0859	.0212						.001	0	5.5	5.3	
TAKEOFF	9.53	1469	73.43	.0431	.0230						0	0	2.2	9.6	
ADVANCED:															
IDLE															
APPROACH															
CLIMBOUT															
TAKEOFF															

ENGINE: CF6-6D
V comb: 2.63 ft^3 T rated: 38900 lbs IDLE POWER: 3.34 % rated
S comb: π_c: 24.7
PRODUCTION

MODE	P_3 (atm)	T_3 (^oR)	$\dot{M}_a$ (#/S)	Ω	f/a						$1-\eta_c$	EI HC	 CO	 NO_x	
IDLE	2.73	783	22.3	.326	.0132						.032	20.5	61.2	4.59	
APPROACH											.0029	1.80	6.00	10.75	
CLIMBOUT											.00066	.60	.60	27.29	
TAKEOFF	24.52	1403	156.6	.0140	.0244						.00066	.60	.60	34.00	
ADVANCED: Double Annular															
IDLE															
APPROACH															
CLIMBOUT															
TAKEOFF															
ADVANCED:															
IDLE															
APPROACH															
CLIMBOUT															
TAKEOFF															

ENGINE: CFM56
V comb: .774 ft^3 T rated: 22,000 lbs IDLE POWER: 4 % rated
S comb: π_c: 24
PRODUCTION

													EI		
MODE	P_3 (atm)	T_3 (^oR)	$\dot{M}_a$ (#/S)	Ω	f/a						$1-\eta_c$	HC	CO	NO_x	
IDLE	2.82	763.9	13.47	.6529	.0147						.0249	9.14	72.85	2.14	
APPROACH	9.97	1094.4	42.41	.1150	.0164						.0016	.29	5.71	7.3	
CLIMBOUT	21.21	1360.6	78.90	.0336	.0246						.0005	0	2.29	16.1	
TAKEOFF	24.14	1417.1	87.64	.0266	.0265						.0005	0	2.29	18.2	
ADVANCED:	Modified comb. with sector burn														
IDLE											.0042	.25	17.3		
APPROACH															
CLIMBOUT															
TAKEOFF															
ADVANCED:															
IDLE															
APPROACH															
CLIMBOUT															
TAKEOFF															

ENGINE: JT3D-7
V comb: 4.86 ft^3 **T rated:** 19000 lbs **IDLE POWER:** 5 % rated
S comb: 29.73 ft^2 π_c: 13.5
PRODUCTION

												EI		
MODE	P_3 (atm)	T_3 (^oR)	$\dot{M}_a$ (#/S)	Ω	f/a					$1-\eta_c$	HC	CO	NO_x	
IDLE	2.04	650	33.89	.5799	.0083					.0818	69.1	91.9	3.3	
APPROACH	5.58	911	91.13	.1572	.0094					.0034	0.5	12.8	8.0	
CLIMBOUT	11.84	1133	168.48	.0497	.0135					.0003	0.1	1.1	14.4	
TAKEOFF	13.61	1185.8	186.86	.0389	.0148					.0002	0.1	0.5	19.1	
ADVANCED:														
IDLE														
APPROACH														
CLIMBOUT														
TAKEOFF														
ADVANCED:														
IDLE														
APPROACH														
CLIMBOUT														
TAKEOFF														

ENGINE: JT8D-17
V comb: 2.70 ft^3 T rated: 16,000 lbs. IDLE POWER: 6 % rated
S comb: 11.65 ft^2 π_c: 16.9
PRODUCTION

												EI			
MODE	P_3 (atm)	T_3 (^oR)	$\dot{M}_a$ (#/S)	Ω	f/a						$1-\eta_c$	HC	CO	NO_x	
IDLE	2.86	742	31.94	.4518	.010						.019	11.4	40.9	4.0	
APPROACH	6.83	964	69.37	.1354	.0112						.003	.80	10.4	8.2	
CLIMBOUT	15.07	1220	133.19	.0390	.0164						.0003	.10	.84	18.6	
TAKEOFF	17.39	1286	150.30	.0301	.0182						.0002	.10	.67	22.7	
ADVANCED:	Aerating nozzle with richer primary zone														
IDLE	2.86	742	31.94	.4518	.010						.0032	.09	13.4	4.24	
APPROACH	6.83	964	69.37	.1354	.0112						.0008	.122	3.16	7.32	
CLIMBOUT	15.07	1220	133.19	.0390	.0164						.0001	.002	.591	17	
TAKEOFF	17.39	1286	150.30	.0301	.0182						.0001	.01	.54	19.95	
ADVANCED:															
IDLE															
APPROACH															
CLIMBOUT															
TAKEOFF															

ENGINE: JT9D-7
V comb: 4.4 ft^3 **T rated:** 45, 500 lbs. **IDLE POWER:** 7 **% rated**
S comb: π_c: 21.7
PRODUCTION

												EI			
MODE	P_3 (atm)	T_3 (^oR)	$\dot{M}_a$ (#/S)	Ω	f/a						$1-\eta_c$	HC	CO	NO_x	
IDLE	3.74	820	37.04	.1710	.0105						.038	25	70	3.2	
APPROACH	8.98	1064	97.22	.0592	.0140						.0033	1.2	10	10.1	
CLIMBOUT	19.18	1330	186.1	.0177	.0206						.0003	.16	.80	22.3	
TAKEOFF	21.7	1384	206.5	.0142	.0226						.0004	.21	1.0	30	
ADVANCED:	VORBIX			V comb=2.93											
IDLE	3.74	820	37.04	.2577	.0105						.0112	3	37	3.7	
APPROACH	6.80	1064	97.22	.1466	.0140						.0049	.9	17.6	7.1	
CLIMBOUT	6.80	1330	186.1	.1716	.0206						.0095	2.9	30	12.1	
TAKEOFF	6.80	1384	206.5	.1722	.0226						.0084	3.0	25	15.7	
ADVANCED:	Aerating nozzle														
IDLE											.0024	.87	6.9		
APPROACH															
CLIMBOUT															
TAKEOFF															

ENGINE: JT10D

V comb: **T rated:** **IDLE POWER:** **% rated**

S comb: π_c:

PRODUCTION

												EI			
MODE	P_3 (atm)	T_3 (^oR)	M_a (#/S)	Ω	f/a						$1-\eta_c$	HC	CO	NO_x	
IDLE															
APPROACH															
CLIMBOUT															
TAKEOFF															
ADVANCED:															
IDLE															
APPROACH															
CLIMBOUT															
TAKEOFF															
ADVANCED:															
IDLE															
APPROACH															
CLIMBOUT															
TAKEOFF															

ENGINE: Spey Mk511

V comb: **T rated:** 11,400 lbs. **IDLE POWER:** 5 **% rated**

S comb: π_c: 19.1

PRODUCTION

MODE	P_3 (atm)	T_3 (^oR)	$\dot{M}_a$ (#/S)	Ω	f/a						$1-\eta_c$	EI HC	EI CO	NO_x	
IDLE											.126	116	105.6		
APPROACH											.0064	2.1	19.7		
CLIMBOUT											.00068	0	2.7		
TAKEOFF											.00046	0	2		
ADVANCED:															
IDLE															
APPROACH															
CLIMBOUT															
TAKEOFF															
ADVANCED:															
IDLE															
APPROACH															
CLIMBOUT															
TAKEOFF															

ENGINE: RB211-22B
V comb:
S comb:
PRODUCTION

T rated: 42,000 lbs
π_c: 25

IDLE POWER: 2 % rated

												EI			
MODE	P_3 (atm)	T_3 (^oR)	$\dot{M}_a$ (#/S)	Ω	f/a						$1-\eta_c$	HC	CO	NO_x	
IDLE				0.33							.090	81.6	80		
APPROACH											.010	5.2	23.5		
CLIMBOUT											.0012	0.3	3.3		
TAKEOFF				0.043							.00013				
ADVANCED:															
IDLE				0.33							.010	5.2	23.5		
APPROACH											.0013	0.3	3.7		
CLIMBOUT															
TAKEOFF				0.043											
ADVANCED:															
IDLE															
APPROACH															
CLIMBOUT															
TAKEOFF															

Appendix B

Analysis of the Format of the Standards

The present aircraft standards can be represented by two multiplicative terms, one representative of the combustor performance (in terms of mass of pollutant per mass of fuel), and the other representative of the fuel consumption efficiency of the engine (in terms of mass of fuel per level of useful output), both terms being weighted over the prescribed landing -takeoff cycle:

$$\text{standard} = (\text{combustor performance}) \times (\text{fuel consumption})$$

or

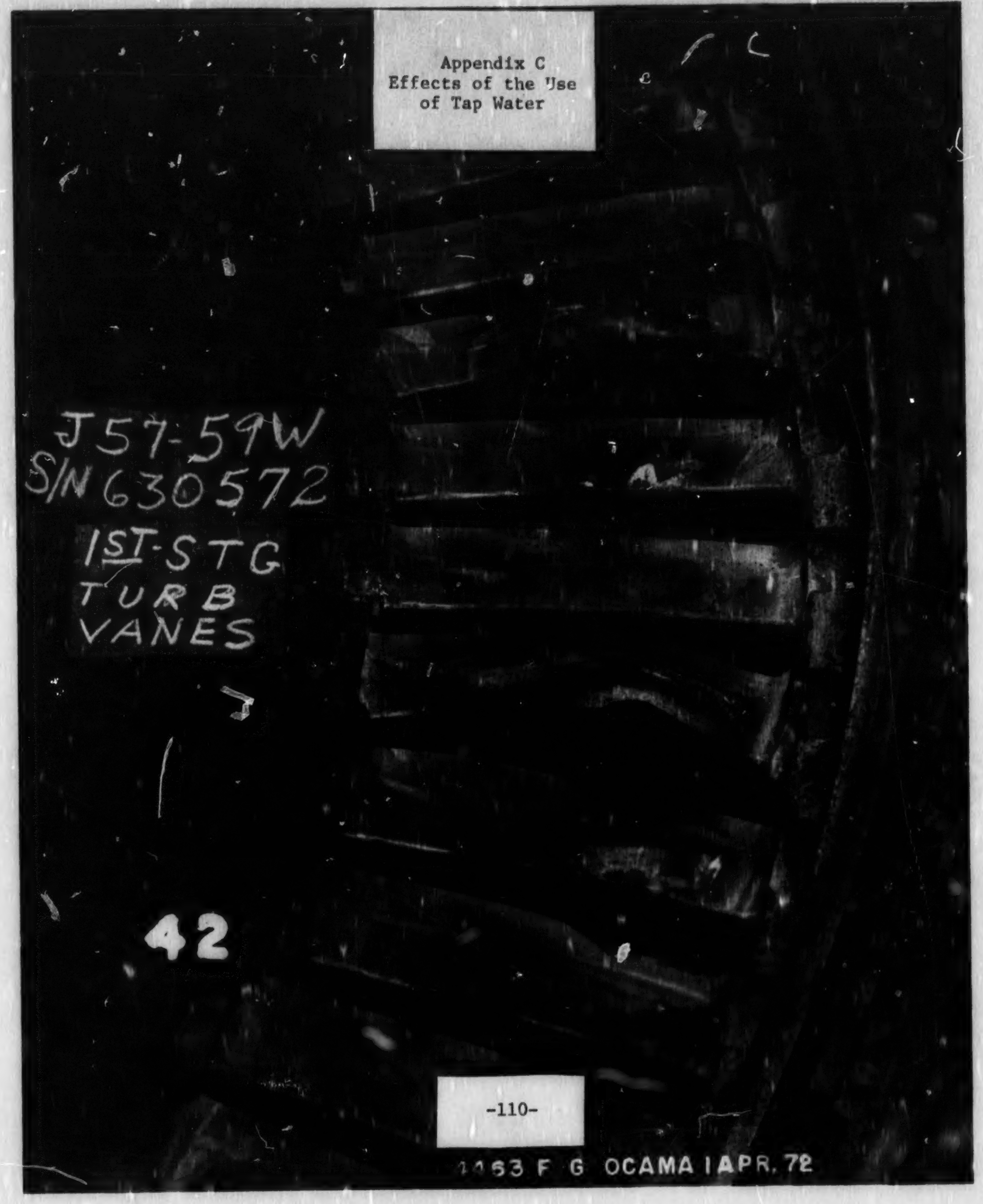
$$\text{standard} = \frac{\text{mass of pollutant}}{\text{mass of fuel}} \times \frac{\text{mass of fuel}}{\text{useful output}} = \text{EI} \times \text{SFC}$$

or simply

$$\text{standard} = \frac{\text{mass of pollutant}}{\text{useful output}}$$

Compliance with the standard can thus be approached in two ways, (1) by improvement of the combustor performance (ie. reducing the emissions index) and (2) by improvement of the fuel consumption efficiency (ie. reducing the SFC). The latter approach is accomplished principally by modification of the thermodynamic cycle of the engine, that is, modification of the compressor pressure ratio and the fan bypass ratio. This standard thus encourages fuel economy through the judicious choice of the thermodynamic cycle of the engine.

However, for engines already in existence, the thermodynamic cycle and hence the SFC is fixed. Therefore compliance with the standards has to be accomplished by improving the combustor emission performance. For engines with low SFC, compliance with the standards will be less difficult than for engines with high SFC. Engines with very high SFC will not be able to meet the standards without the use of exotic technology (eg., catalysts) which is still in the exploratory stage.


J57-59W
S/N 630572
1ST-STG
TURB
VANES
42
1463 F G OCAMA 1APR. 72